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ISBN

9798189278938

Author

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Publication Date

2026-05-01

Peer reviewed|Thesis/dissertation

Exomoons to ExoEarths:
Pathways Toward Habitable Worlds Around Sun-like Stars

By

Caleb Kenji Harada

A dissertation submitted in partial satisfaction of the
requirements for the degree of

Doctor of Philosophy

in

Astrophysics

in the

Graduate Division

of the

University of California, Berkeley

Committee in charge:

Professor Courtney D. Dressing, Chair
Professor Jennifer B. Bergner
Professor Eugene Chiang

Spring 2026

Exomoons to ExoEarths:
Pathways Toward Habitable Worlds Around Sun-like Stars

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By

Caleb Kenji Harada

Abstract

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The origin and evolution of our Solar System, our home planet, and our species are mysteries that depend on a rich, complex history of stochastic formation processes. The discovery of planets orbiting other stars beyond the Solar System challenged canonical wisdom on how and when these processes might have unfolded, signaling a paradigm shift in how we see the Earth, life, and ourselves in relation to the Cosmos. The past 30 yr of exoplanet discovery have continued to reveal an overwhelming diversity of planetary properties, host stars, and environments that are completely unlike the Solar System, leading to more questions than answers in how planets and life may emerge. In this dissertation, I present theoretical simulations and multi-technique observations of exoplanets and their host stars to investigate of how planetary systems similar to ours form, evolve, and become habitable.

First, I report on the first investigation of potentially habitable exomoons in the HIP 41378 multi-planet system. I present `astroQTPy`, an open-source Python package that uses a quadtree framework to accelerate N -body experiments for hierarchical star-planet-moon systems. Applying this package to the planet HIP 41378 f, a temperate Jovian in the optimistic habitable zone of its host star, I simulate plausible exomoon properties and orbits that are consistent with space-based transit observations from the K2 mission and Hubble Space Telescope (HST). Combining these simulations with tidal evolution simulations and photodynamical transit models, I show that long-term stable, Earth-sized moons around HIP 41378 f are dynamically viable and consistent with observations. Therefore, this planet is a promising laboratory for testing theories of exomoon formation and habitability in the era of extremely-high-precision photometry with the James Webb Space Telescope (JWST) and PLATO (PLANetary Transits and Oscillations of stars).

Next, I discuss ways in which stars are interconnected with planetary habitability and present a catalog of key stellar parameters of nearby stars. I analyze the FUV–MIR spectral energy distributions of nearby FGKM stars using Bayesian model averaging to derive robust stellar parameters (e.g., T_{eff} , $L_{\star}$) that are relevant to planetary habitability. I present a public catalog that integrates

these stellar parameters with flare rates and optical variability from the Transiting Exoplanet Survey Satellite (TESS), X-ray fluxes, and stellar abundance from the literature. This critical dataset informs the selection of high-priority targets for future exoplanet direct-imaging missions like the Habitable Worlds Observatory (HWO) by providing essential inputs for modeling rocky planet interiors, out-gassed atmospheres, and global biosignatures.

Then, I present a deep archival radial velocity (RV) search of > 100 nearby Sun-like stars to explore the range of planetary architectures and evolutionary pathways where habitable exoplanets could exist. I discuss the inception and outcomes of a community science project involving > 60 participants, which assembled over 150,000 archival RV measurements from 23 spectrographs spanning 36 yr to constrain companion masses and orbits, identify new Keplerian signals, and measure sensitivity as a function of minimum mass and semi-major axis. The community science project (called the “SPORES-HWO RV Hunters”) revealed that current RV data remain insensitive to Jupiter-like giant analogs in $\sim 50\%$ of these nearby systems and typically probe only planets $\gtrsim 50 M_{\oplus}$ in the habitable zone. This motivates additional long-baseline RV monitoring to constrain the architectures of these systems, identify dynamically disruptive companions, and provide planetary system context that will enable future searches for habitable worlds with space-based direct imaging.

Finally, I present preliminary results from new RV observations targeting nearby Sun-like stars previously overlooked in exoplanet surveys. I discuss new evidence for at least one eccentric giant companion orbiting a high-priority HWO direct-imaging target in the habitable zone. Such giant planets may be dynamically incompatible with Earth-like habitable zone planets, and are therefore necessary to constrain prior to direct-imaging exoEarth surveys to maximize efficiency. This potential planet discovery demonstrates how systematic follow-up of neglected systems continues to uncover key missing pieces of the local planetary census.



To my family — by blood and by choice.

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Preface



This dissertation was written by a human being. No generative artificial intelligence (AI) or large language models (LLMs) were used at any stage of creating the work presented here.

Acknowledgments



This dissertation was made possible by countless people and organizations whom I am immensely grateful for. I grateful for the mentorship and wisdom of my Ph.D. advisor, Prof. Courtney Dressing. Thank you for the opportunities you've given me. I would also like to acknowledge the guidance of my graduate academic advisor, Prof. Dan Weisz, as well as the members of my dissertation committee, Prof. Jenny Bergner and Prof. Eugene Chiang. I owe an especially big thank you to my incredible collaborators and mentors Prof. Stephen Kane and Prof. Natalie Hinkel, without whom I could not have crossed the finish line to earn this degree. Your compassionate support truly kept me going through some of the hardest parts of graduate school. I also greatly appreciate all of the conversations (about science and about life) I had with my colleagues and mentors Dr. Jenn Burt, Prof. David Charbonneau, Dr. Jessie Christiansen, Dr. David Ciardi, Prof. Jonathan Fortney, Dr. Eric Mamajek, Prof. Malena Rice, Prof. Andrew Vanderburg, Prof. Jason Wang, and Prof. Rob Wittenmyer.

I am grateful to have had financial support throughout most of my Ph.D. from National Science Foundation (NSF) Graduate Research Fellowship Program (GRFP) under Grant No. DGE 2146752. I am also thankful for support from the NASA Astrophysics Decadal Survey Precursor Science (ADSPS) program under Grant No. 80NSSC23K1476 (awarded to C. D. Dressing and S. R. Kane). Portions of this research were also supported by the David & Lucile Packard Foundation under Grant 2019-69648 (awarded to C. D. Dressing). Portions of this research made use of observations from the NASA/ESA Hubble Space Telescope (HST), obtained at the Space Telescope Science Institute (STScI), which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS 526555. The HST observations presented in Chapter 2 are associated with HST-GO program 16267 (PI: Dressing), and the analysis was supported by grant HST-GO-16267.

I thank my fellow graduate students at UC Berkeley (and especially my COVID-19 cohort) for making the department feel like a place of community, rather than just a place of work. In particular, I want to highlight my fellow PALS research group members, Ella Chevalier, Charles Fortenbach, Steven Giacalone, Andy Mayo, and Emma Turtelboom, for their collaborative spirit, willingness to help others, and emotional support during times of despair (and times of joy). I am also extremely grateful for all the support staff in the UC Berkeley Astronomy Department whose diligent work behind the scenes made my time in graduate school run as smoothly as possible: Bill Boyd, Shirlin Dudonis, Brianna Franklin, Brandye Johnson, Maria Kies, Ann Oakenfull, Brad Perl, Yasasha Ridel, and Anthony Vitan. Whether it was helping to fix a classroom projector at the last minute or simply putting a smile on my face when we crossed paths in the hallway, your commitment to the people in our department is inspiring.

I would not have made it this far without so many amazing teachers and mentors who inspired me to pursue a graduate degree in astronomy and gave me the tools to make that dream into a reality. To every one of my undergraduate research advisors—Prof. Drake Deming, Prof. Ben Montet, Prof. Antonija Oklopčić, Prof. Emily Rauscher, and Prof. Eliza Kempton—thank you for

your invaluable mentorship and for believing in me throughout all the growing pains of learning how to do research. I owe a special thank you to Elizabeth Warner at the University of Maryland Observatory for letting me volunteer at open house nights and ultimately work my way up to my very first research experience observing exoplanet transits as part of the KELT Follow-up Network. Drake, Ben, and Emily, thank you for taking a chance on me when I emailed you asking for research opportunities when I had no idea what I was doing. I am especially grateful for my undergraduate academic advisor Dr. Melissa Hayes-Gehrke and my very first astronomy professor (and birdwatching coach!) Prof. Derek Richardson for their guidance and support throughout college. I also extend my sincere thanks and appreciation to Dr. Matt Ashby, Dr. Jonathan McDowell, and all of the support staff who helped organize the 2019 REU at the Smithsonian Astrophysical Observatory, without which I would not be where I am today.

I am incredibly thankful for my colleagues/friends Sarah Blunt, Casey Brinkman, Jamie Dietrich, Victoria DiTomasso, Kyle Franson, Arvind Gupta, Michelle Hill, Zhexing Li, Isaac Malsky, Kristo Ment, August Muench, Emily Pass, Romy Rodriguez, Sabina Sagynbayeva, Noah Tuchow, and Austin Ware for their advice, feedback, and helpful discussions that improved my research and helped me grow as a scientist. I am grateful to the hundreds of scientists who proposed for and collected the archival observations that made portions of this research possible. Thank you to all of the SPORES-HWO RV Hunters volunteers whose hard work made portions of this research possible: Lubna Alrubayyi, Nouran Alyousif, Aaliyah-Tiffany Anderson, Jeremy Baden, Griffin Beckman, Paul Beroza, Kobe Bilstad, Diego Bonilla, Shep Brooke, Linus Buchholz, Christopher Chin, Kyle Chuon, Jose Farias-Ramirez, Aidan Fernandez, Celeste Gomez, Chase Graham, Paige Haworth, Sarah Jauregui, Krish Jhurani, Sean Johnson, Nathanael Kanter, Myra Khieu, Pranathi Kolla, Shivani Kulkarni, Kaitlyn Le, Allison Lew, Emerald Lin, Melanie Linares, Nykole Liu, Remy Liu, Leslie Lopez, Yugandhara Luthra, Brayden Matejka, Rosendo Medina-Uribe, Austin Mei, Abhi Nathan, Trevor Nguyen, Raiki Omori, Arjun Patel, Halim Perez Melendez, Brandon Pestoni, Ava Phillips, Aakarsh Real, Colin Smith, Max Steiman, Chienyu Sun, Gavin Tamasi, Vivian Tamayo, Caitlin Tran, Alaina Tripp, David Trujillo, Flora Wang, Alana Waterman, Dylan Yamzon, Bobby Yuan, and Adam Zbriger. I also wish to thank the anonymous peer reviewers and editors at AAS Journals for their service to the community.

I also sincerely thank all of my wonderful co-authors for their important contributions and conversations that made this research possible. They are acknowledged at the beginning of each chapter. I am grateful for the many funding agencies that have provided support for our collaborative work, including: Agencia Estatal de Investigación (AEI); the Cal-Bridge Summer Research Program; the European Union Horizon 2020 Research and Innovation Programme; the European Union NextGenerationEU PRTR; the European Research Council (ERC) FIERCE; Fundação para a Ciência e a Tecnologia (FCT); Fundación la Caixa; the Heising-Simons Foundation; Le Centre National d'Études Spatiales (CNES); the National Aeronautics and Space Administration (NASA); the National Science Foundation (NSF); Programme National de Planétologie (PNP) of CNRS-INSU, co-funded by CNES; Programa Operacional Competitividade e Internacionalização (COMPETE 2020); the Ramón y Cajal Programme; the UK Science and Technology Facilities Council (STFC); and the UK Space Agency.

This research made use of the NASA Exoplanet Archive, which is operated by the Califor-

nia Institute of Technology, under contract with NASA under the Exoplanet Exploration Program, and the Astrophysics Data System (ADS), funded by NASA under cooperative agreement 80NSSC25M7105. This research includes data collected by the Kepler and TESS missions and obtained from the Mikulski Archive for Space Telescopes (MAST) data archive at STScI. Funding for the Kepler mission is provided by the NASA Science Mission Directorate. Funding for the TESS mission is provided by the NASA Explorer Program. This research has made use of the SIMBAD database and the VizieR catalog access tool, CDS, Strasbourg Astronomical Observatory, France (doi:10.26093/cds/vizieR). This research also makes use of The Data & Analysis Center for Exoplanets (DACE), which is a facility based at the University of Geneva (CH) dedicated to extrasolar planet data visualization, exchange, and analysis. DACE is a platform of the Swiss National Centre of Competence in Research (NCCR), federating the Swiss expertise in Exoplanet research. The DACE platform is available at <https://dace.unige.ch>. This research uses data from the European Space Agency (ESA) mission Gaia (<https://www.cosmos.esa.int/gaia>), processed by the Gaia Data Processing and Analysis Consortium (DPAC, <https://www.cosmos.esa.int/web/gaia/dpac/consortium>). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This research makes use of the Washington Double Star (WDS) Catalog maintained at the U.S. Naval Observatory, in addition to the International Variable Star Index (VSX) database, operated at AAVSO, Cambridge, Massachusetts, USA. The research presented in Chapter 3 made use of the Hypatia Catalog Database, an online compilation of stellar abundance data as described in Hinkel et al. (2014), which was supported by NASA’s Nexus for Exoplanet System Science (NExSS) research coordination network and the Vanderbilt Initiative in Data-Intensive Astrophysics (VIDA). This research used the Savio computational cluster resource provided by the Berkeley Research Computing program at the University of California, Berkeley (supported by the UC Berkeley Chancellor, Vice Chancellor for Research, and Chief Information Officer).

The field of astronomy today would not be possible without the vital contributions of researchers who publicly release well-documented and high-quality research software. The following open-source codebases were used in this work: ARIADNE (Vines and Jenkins 2022); Astropy (Astropy Collaboration et al. 2013, 2018); AstroQTPy (Harada 2023); *celerite* (Foreman-Mackey et al. 2017; Foreman-Mackey 2018); *corner* (Foreman-Mackey 2016); *dynesty* (Speagle 2020); *emcee* (Foreman-Mackey et al. 2013); *exoplanet* (Foreman-Mackey et al. 2021a,b); *EqTide* (Barnes 2017); *ExoTiC-LD* (Wakeford and Grant 2022); *IPython* (Perez and Granger 2007); *isochrones* (Morton 2015a); *juliet* (Espinoza et al. 2019); *Lightkurve* (Lightkurve Collaboration et al. 2018); *Matplotlib* (Hunter 2007); *NumPy* (Van Der Walt et al. 2011; Harris et al. 2020); *Pandas* (The pandas development Team 2025); *Pandora* (Hippke and Heller 2022); *PLATON* (Zhang et al. 2019, 2020); *RadVel* (Fulton et al. 2018); *REBOUND* (Rein and Liu 2012; Rein and Spiegel 2015); *RVSearch* (Rosenthal et al. 2021); *SciPy* (Virtanen et al. 2020); *UltraNest* (Buchner 2021). I also want to shout out to the wonderful organizers and TAs at Code/Astro (especially Sarah Blunt and Jason Wang) for their game-changing workshop at Northwestern CIERA bringing open-source coding to the masses.

This research was made possible by the following facilities: AAT (UCLES); ADS; APF (Levy); CAO:3.5m (CARMENES); CDS; CTIO:1.5m (CHIRON, Fiber Echelle); ESO:3.6m (CES-LC,

CES-VLC, HARPS); Euler1.2m (CORALIE); ExoFOP; Exoplanet Archive; FLWO:1.5m (AFOE); Gaia; GALEX; HET (HRS); HIPPARCOS; HST (WFC3); Keck:I (HIRES); Kepler; LDT (EX-PRES); Magellan:Clay (PFS); MAST; OHP:1.93m (ELODIE, SOPHIE); Shane (Hamilton); Smith (Tull); TESS; TNG (HARPS-North); VLT:Kueyen (ESPRESSO, UVES); WISE; WIYN (NEID). I extend my utmost appreciation to the HARPS team and all the PIs and observers associated with the many ESO programs and data sets used in Chapter 4. The same goes to all of the PIs and observers who contributed HIRES data to the Keck Observatory Archive (for a list of PI names, please see Butler et al. 2017). This work is in part based on observations collected at the European Organization for Astronomical Research in the Southern Hemisphere under the ESO programs listed in the acknowledgments of Trifonov et al. (2020). Some of the data presented herein were obtained at Keck Observatory, which is a private 501(c)3 nonprofit organization operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. This research has also made use of the Keck Observatory Archive (KOA), which is operated by the W. M. Keck Observatory and the NASA Exoplanet Science Institute (NExSci), under contract with the National Aeronautics and Space Administration.

I respectfully acknowledge all of the indigenous peoples whose lands have been exploited to build many of these observatories, and which have made this research possible. I especially wish to recognize and acknowledge the significant cultural role and reverence that the summit of Maunakea has always had within the Native Hawaiian community. The astronomical community is most fortunate to have the opportunity to conduct observations from this sacred mountain belonging to the Native Hawaiian People. Furthermore, I wish to recognize that Berkeley and Oakland sit on the territory of xučyun (Huichin), the ancestral and unceded land of the Chochenyo speaking Ohlone people, the successors of the historic and sovereign Verona Band of Alameda County. This land was and continues to be of great importance to the Muwekma (Muh-wek-muh) Ohlone Tribe and other familial descendants of the Verona Band. I recognize that I and every member of the UC Berkeley community has benefited, and continues to benefit, from the use and occupation of this land since the university's founding in 1868. We have a responsibility to acknowledge and make visible the university's and the greater East Bay community's relationship to Native peoples.

Last but not least, this dissertation would not exist without the steadfast support of my family and friends. Jacob—your love and kindness is truly what kept me going through grad school. I love you so much and can't wait to see what amazing things we will accomplish in the future. I also could not have written this dissertation without our adorable/insane little gremlin baby Katsu (aka Chashu, aka Kitty). To my family, Mom, Dad, Nate, and Noelle, I could not have done this without you. Thank you for always having my back, lifting me up when I was down, and providing endless encouragement. Kari, Alan, and Alyse, I'm so lucky to be able to call you family too. Thank you for always believing in me and inviting us over to watch the 2024 solar eclipse from your backyard! To Granny and ReiRei, you two are my heroes. Thank you for teaching me love as well as strength and resilience. And to all of my Harada/Berman/Regier extended family, I appreciate each and every one of you and love you endlessly. To my undergrad family, Mackenzie, Claire, Kris, Meghna, Melanie, and Alison, I love you all so much and I am so proud of everything we've

been able to accomplish since graduating (go Terps!).

I owe a special shout out to Kyle Ryan (and Miss Oatmeal) for their emotional support during the COVID-19 lockdown when we were quarantined together. Thank you for the many laughs and fun evening with Bonchon and Drag Race. Nick Dong and Isaiah Escobar-Henry, thank you for all the fun times we had in the Castro and on your chartered party boats. I will cherish those memories forever. Deryl Long, Jea Adams, Zoe de Beurs, and Dakota Tyler, thank you for being my summertime besties during those summer REUs—with luck, I’m sure our paths will cross again in the future. Emma Turtelboom, Andy Mayo, and Steven Giacalone thank you for being my PALS 4 life. Nice Choksi, thanks for the burrito recommendations (wheat and wet). Maude Gull, thank you for your kindness and for being the photographer at my wedding. Aliza Beverage and Massimo Pascale, thank you for being my older grad school siblings and helping me navigate academia when I was Going Through It. To all my endlessly inspiring and beautiful friends in AstroQ (you know who you are), thank you so much for giving me a community on campus where I felt truly welcomed and appreciated. I hope we always keep in touch. Finally, thank you to all of the local and family businesses in Berkeley and Oakland that have kept me fueled up to complete this dissertation: Timeless on 17th, Fresh and Best II, Sconehege, El Talpense, Nido’s Backyard, Berkeley Bowl, and of course Momo Masala.

Chapter 1

Background

For millennia, humans have speculated and debated over the existence of other worlds and whether we are alone. Our earliest human ancestors surely would have been *aware* of the 5 wandering points of light in the night sky that we know today as the planets in our solar system (Uranus and Neptune remained undiscovered until the 18th and 19th centuries), but those wandering points would have been just as mysterious to them as the Sun, the Moon, and the stars. Ancient philosophers, whose sharpest telescopes were mere imagination, could no better constrain the true nature of the planets than determine whether or not we were at the center of the universe. Opinions ranged from “*There are infinite worlds both like and unlike this world of ours*” (Epicurus, 341–270 BCE) to “*There cannot be more worlds than one*” (Aristotle, 384–322 BCE). It wasn’t until the Scientific Revolution in the 16th and 17th centuries CE that the ideas that the Earth might not be the center of the universe and that the planets could in fact be other worlds started to gain traction.

We have now sent dozens of robotic spacecraft to other worlds in our solar system and discovered over 6,270 exoplanets orbiting other stars¹ (Christiansen et al. 2025). Today, exoplanet research remains one of the most rapidly developing subjects in astronomy and advances in technology are poised to continue this upward trend over the coming decades. And, after millennia of speculation, we are now on the precipice of being able to scientifically address the question of whether life exists elsewhere in the universe.

This dissertation aims to bridge our current knowledge of exoplanetary systems that we have gained over the past ~ 30 yr to future discoveries of extrasolar worlds that new technology will enable—including potentially Earth-like planets orbiting Sun-like stars. In this chapter, I provide background context for the subjects discussed throughout the remainder of this dissertation. I first review the primary methods of detecting planets around solar-type stars in Section 1.1 (note that I will use the terms “planet” and “exoplanet” interchangeably throughout this work). Then, I discuss planetary habitability in Section 1.2. I provide additional background on the search for extrasolar life and the future facilities that will drive it in Section 1.3. Lastly, I provide a summary of the research presented in subsequent chapters of this dissertation and additional work that had progressed alongside it in Section 1.4.

¹NASA Exoplanet Archive, last accessed 23 April 2026: <https://exoplanetarchive.ipac.caltech.edu>

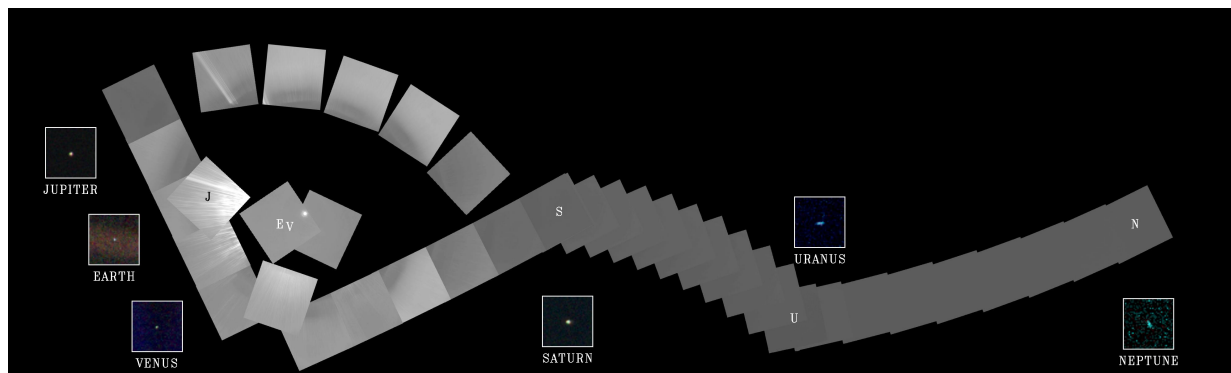


Figure 1.1: The First-Ever Solar System Family Portrait (1990). This mosaic shows the final series of 60 images captured by NASA's Voyager 1 spacecraft as it was speeding out of our solar system. Six of our solar system's planets are visible. *Credit: NASA/Jet Propulsion Laboratory-Caltech.*

1.1 Detecting Exoplanets Around Sun-like Stars

Shining by reflected starlight, exoplanets analogous to the planets in the Solar System (Figure 1.1) will be at least billions of times fainter than their host stars and, depending on their distance, only tens of arcseconds away in angular separation. This combination makes exoplanets extremely challenging to photograph directly in optical wavelengths. Alternative detection methods, based on direct measurements of the host star rather than the planet itself, have proven to be much more fruitful. In 1992, the first reliable detection of planetary-mass objects beyond the solar system was achieved by measuring radio pulse timing variations of a rapidly rotating neutron star (Wolszczan and Frail 1992). The first suggestions of sub-stellar objects orbiting main-sequence stars were made in 1988 using high-accuracy radial velocity (Doppler) measurements (Campbell et al. 1988; Latham et al. 1989), with the first unambiguous detection being reported in 1995 with the discovery of 51 Pegasi b (Mayor and Queloz 1995). In this dissertation, I primarily discuss two exoplanet detection methods, namely, the transit method and the radial velocity method, which have been used to discover the majority of confirmed exoplanets known today. I will also discuss direct imaging in the context of future facilities that will leverage advances in technology to detect Earth-size planets around Sun-like stars, analogous to the Voyager 1 image shown in Figure 1.1. Other detection methods (e.g., pulsar timing, transit timing variations, astrometry, microlensing) are no less important or interesting, but are not as relevant to the work presented here.

Radial Velocities

While the basic concept behind detecting exoplanets using the radial velocity (RV) method is straightforward, over 4 decades went by from the time it was first proposed (Struve 1952) to the first confirmed detection of an exoplanet around a main-sequence star (Mayor and Queloz 1995). The idea is that a planet in orbit around a star causes the star to undergo reflex motion about the system's barycenter (center of mass). The star's reflex motion along the line of sight can then be

measured as a spectroscopic Doppler shift, which varies with a period equal to the planet’s orbital period, P . Assuming we know the mass of the host star, $M_\star$, through other means (e.g., matching stellar atmospheric models to high-resolution spectra), Kepler’s Third Law can then be applied to infer the planet’s semimajor axis, a .

It can be shown from Kepler’s laws and the conservation of momentum that the semi-amplitude, K , of the RV variations depends on P , $M_\star$, and the mass of the planet, M_p . For non-circular orbits, K also depends on the eccentricity, e :

$$K = \left(\frac{2\pi G}{P} \right)^{1/3} \frac{M_p \sin i}{(M_p + M_\star)^{2/3}} \frac{1}{\sqrt{1 - e^2}}, \quad (1.1)$$

where G is the gravitational constant. For a fixed K , note that M_p is degenerate with the orbital inclination, i , which is often unknown for planets that do not transit. RV time series measurements spanning at least one complete orbit will therefore allow us to determine the planet’s mass (up to a factor of $\sin i$) from K , P , and e (if sufficient data are available), assuming the host star mass is known.

For virtually all planets, $M_p \ll M_\star$, allowing us to write down a useful approximation (for circular orbits) in terms of familiar quantities:

$$K = 28.4 \text{ m s}^{-1} \left(\frac{P}{1 \text{ yr}} \right)^{-1/3} \left(\frac{M_p \sin i}{M_J} \right) \left(\frac{M_\star}{M_\odot} \right)^{-2/3}. \quad (1.2)$$

For reference, Jupiter orbiting the Sun ($P = 11.9 \text{ yr}$) would produce an RV semi-amplitude of $K_J = 12.5 \text{ m s}^{-1}$. Earth orbiting the Sun would produce $K_\oplus = 0.09 \text{ m s}^{-1}$.

At optical wavelengths ($\lambda = 550 \text{ nm}$), the Doppler shifts produced by these motions are $\Delta\lambda = 2.3 \times 10^{-5} \text{ nm}$ (22.9 fm) and $\Delta\lambda = 1.6 \times 10^{-7} \text{ nm}$ (0.16 fm), respectively. Measuring such tiny signals with an adequate signal-to-noise ratio (SNR) requires a stable, high-dispersion spectrograph ($R \equiv \lambda/\Delta\lambda \gtrsim 50,000$), many absorption lines, and a lot of photons (i.e., a large telescope aperture and/or a bright host star). This has been achieved by dispersing the starlight in both the horizontal and vertical directions on a CCD (charge coupled device) using high-accuracy échelle (or “ladder”) spectrographs, with early examples including the Lick Observatory Hamilton spectrometer (Vogt 1987), the High Resolution Echelle Spectrometer (HIRES) at Keck (Vogt et al. 1994), and ELODIE at the Observatoire de Haute-Provence (Baranne et al. 1996). These first-generation échelle spectrographs were capable of reaching RV precisions of $\sim 10 \text{ m s}^{-1}$.

Subsequent iterations of échelle instruments included the High Accuracy Radial Velocity Planet Searcher (HARPS) on ESO’s 3.6 m Telescope at La Silla Observatory (Mayor et al. 2003), HARPS-N on the Galileo National Telescope (Cosentino et al. 2012), the Automated Planet Finder (APF) at Lick Observatory (Vogt et al. 2014), the University College London Échelle Spectrograph (UCLES) on the Anglo-Australian Telescope, and the Planet Finder Spectrograph (PFS) on Magellan II (Crane et al. 2010), which achieved RV precisions of $\sim 1\text{--}3 \text{ m s}^{-1}$. Today’s cutting-edge “extreme” precision RV (EPRV) spectrographs routinely achieve precisions of $\sim 0.3\text{--}1 \text{ m s}^{-1}$, with the gold standard goal of reaching 10 cm s^{-1} precision in order to detect Earth-mass planets on 1 yr

orbits around Sun-like stars. Some examples include the Échelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) on ESO’s Very Large Telescope (Pepe et al. 2021), the EXtreme PREcision Spectrograph (EXPRES) on the Lowell Discovery Telescope (Blackman et al. 2020), the NN-EXPLORE Exoplanet Investigations with Doppler Spectroscopy (NEID) Spectrograph on the 3.5 m WIYN telescope (Schwab et al. 2016), and the Keck Planet Finder (KPF) on Keck² (Gibson et al. 2016). Additional examples of échelle spectrographs are discussed in Chapter 4 and listed in Table 4.A2.

Reliable wavelength calibration is another prerequisite for high-accuracy RVs. Iodine (I_2) gas cells are common in many planet-searching instruments, including HIRES, UCLES, and Lick–Hamilton (e.g., Koch and Woehl 1984; Butler and Marcy 1996). The gas cell is placed in the optical path of the telescope just before the spectrograph slit, causing I_2 absorption lines of known wavelength to be superimposed on the stellar spectrum. The I_2 gas cell produces thousands of absorption lines, allowing for an accurate wavelength solution, while also tracking changes to the instrument point-spread function due to the shared optical path with the starlight. However, this has the disadvantage of reducing optical throughput. As an alternative to I_2 cells, thorium–argon (Th–Ar) emission lamps have also been used for wavelength calibration (e.g., HARPS, ELODIE). In this case, two separate optical fibers are fed into the spectrograph: one for starlight and the other for the Th–Ar reference spectrum. Th–Ar lamps have the advantage of producing a large number of spectral emission features over a broad wavelength range without reducing throughput. Even more reliable wavelength solutions have been achieved recently using laser frequency combs (LFCs), which produce individual emission lines of uniform spacing and intensity whose wavelengths are precisely determined from fundamental physics (e.g., Murphy et al. 2007). EXPRES is one example of an EPRV instrument that uses LFC for wavelength calibration (Blackman et al. 2020).

To date, a total of 1,179 planets have been confirmed via RV detection (Christiansen et al. 2025). The confirmed RV planets whose masses (or $M_p \sin i$) are known to 25% precision or better are displayed as blue circles in the mass–period plot shown in Figure 1.2. Early expectations of what astronomers expected exoplanetary systems to look like, which had been informed by Solar System observations, were immediately challenged when the first unambiguous RV exoplanet detection was a Jupiter-mass object orbiting its host star with a period of only 4.23 days (Mayor and Queloz 1995). As Figure 1.2 demonstrates, very few exoplanets discovered since then resemble anything like the planets in our solar system. For example, the population of hot Jupiters (i.e., planets similar in mass to Jupiter with orbital periods $\lesssim 10$ days) in the upper left quadrant prompted an urgent reexamination of conventional theories of giant planet formation and evolution (e.g., Pollack et al. 1996; Weidenschilling and Marzari 1996; Boss 1997). Interestingly, despite the large number of these objects in Figure 1.2, the intrinsic frequency (occurrence rate) of hot Jupiters around Sun-like stars is actually relatively low ($\sim 1\%$), owing to observational bias (e.g., Wright et al. 2012). This is because larger and more massive planets on shorter orbital periods are simply easiest to detect ($K \propto P^{-1/3} M_p$). However, with the cumulative baseline of RV observations

²Note: at the time of writing, KPF has yet to demonstrate the long-term stability required for EPRV planet detection (Gibson et al. 2024; Halverson et al., in prep).

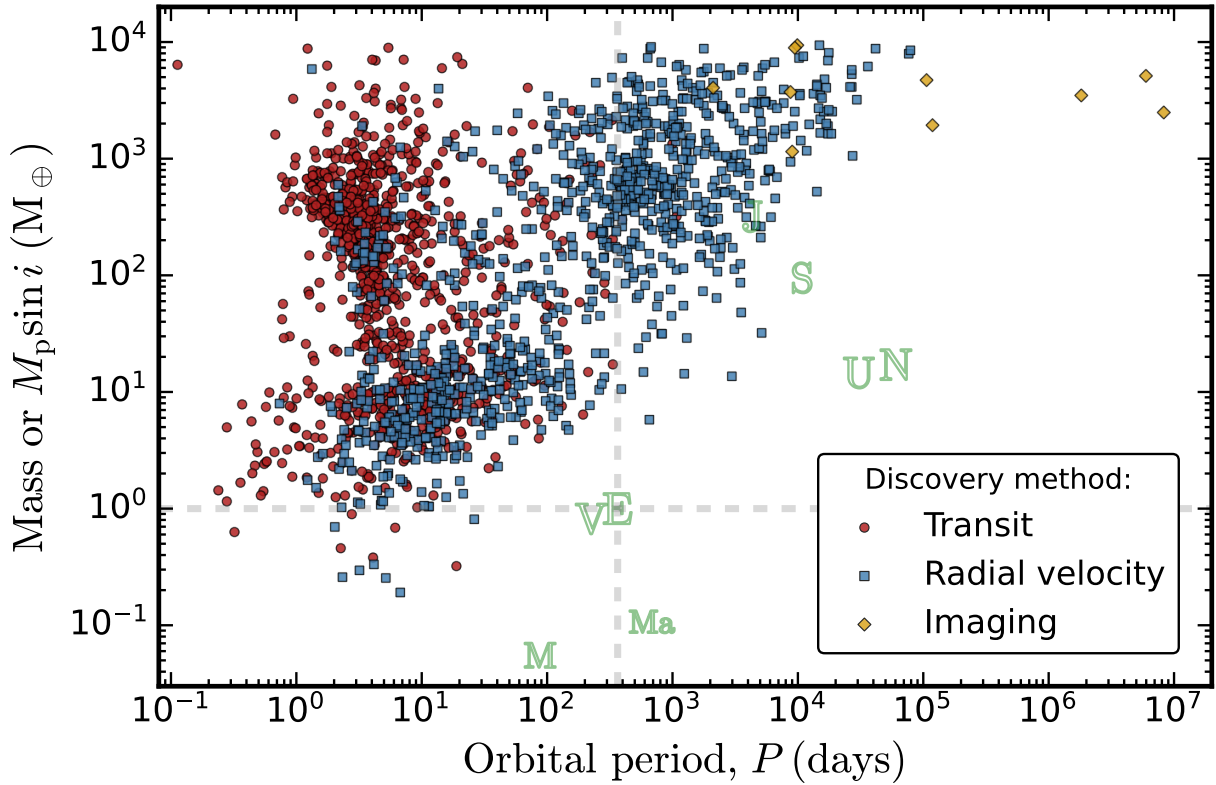


Figure 1.2: Mass–period diagram of confirmed exoplanets whose masses (or $M_p \sin i$) have been measured to a precision of at least 25%. Planets detected via transit, radial velocity, and imaging are plotted as red circles, blue squares, and yellow diamonds, respectively. The Solar System planets are labeled for reference. Data were obtained from the NASA Exoplanet Archive (Christiansen et al. 2025), accessed on 30 April 2026.

now reaching multiple decades, significant progress has been made in detecting massive planets on much longer orbits (the “cold” Jupiters; e.g., Fernandes et al. 2019; Wittenmyer et al. 2020; Fulton et al. 2021). Long-baseline RVs are currently the best method for measuring cold Jupiters (see Figure 1.2), but forthcoming advances in other detection methods—including microlensing (e.g., the Nancy Grace Roman Space Telescope) and high-precision astrometry (e.g., Gaia DR4 and subsequent releases)—will soon add many more planets to this growing population beginning as early as December 2026.

A persistent challenge in RV detection is being able to distinguish between signals produced by planets and those produced by stars. One concern is that the planet mass one can obtain from Equation (1.1) is degenerate with $\sin i$, meaning that solving for M_p will only yield a lower limit (a more inclined system with a more massive companion will produce the same K as an edge-on system with a lower-mass companion). Assuming that all system orientations are uniformly distributed, it can be shown that the probability of any system having an inclination between θ_1 and θ_2 is $P(\theta_1 < i \leq \theta_2) = \int_{\theta_1}^{\theta_2} \sin i \, di$, implying that we should expect the degeneracy to be less than a

factor of 2 in most ($\sim 87\%$) cases. Nonetheless, it has been shown that breaking the $\sin i$ degeneracy through independent measurements of i (e.g., high-precision astrometry) can reveal that objects previously thought to be planets are in fact stellar in nature (e.g., Venner et al. 2021). Another concern, especially for low-SNR signals, is confusion with stellar activity. Magnetic activity in the stellar atmosphere, stellar oscillations, and surface granulation (or other systematics) can all contribute to RV “jitter” or even produce periodic signals with amplitudes and timescales very similar to those produced by a planet (e.g., Bouchy and Carrier 2001; Dumusque et al. 2011a,b,c; Isaacson et al. 2024). Surface inhomogeneities (starspots, plages) that can produce false-alarm planet signals are correlated with stellar chromospheric activity, which can be diagnosed through additional measurements. For example, emission in the core of the Ca II H/K lines is a useful proxy for chromospheric activity, often reported as R'_{HK} or the related Mount Wilson S -index (e.g., Wilson 1968; Middelkoop 1982; Duncan et al. 1991). Stellar activity is a primary concern of state-of-the-art EPRV instrument teams as these signals are present in Sun-like stars at the $\lesssim 1 \text{ m s}^{-1}$ level, comparable to the expected amplitude of Earth-mass exoplanets. Current research (e.g., Sun-as-a-star observations) seeks to better understand the driving physics behind these signals and come up with strategies to mitigate them in future EPRV searches for rocky planets (e.g., Meunier et al. 2015; Haywood et al. 2016; Lin et al. 2022; Rubenzahl et al. 2023).

Transits

A transit occurs when another planet passes within the line of sight between Earth and a star, creating an apparent drop in stellar brightness caused by the transiting planet’s shadow. In the Solar System, transits of the Sun by the planets Mercury and Venus were first predicted by Johannes Kepler in 1630 and first observed later that decade in 1631 and 1639, improving our knowledge of the distances between objects in the Solar System (van Helden 1976; Kollerstrom 2005). In other star systems, planets transit their host stars if their orbits are aligned approximately edge-on with our line of sight, resulting in small but measurable dips in the star’s brightness that occur once per planetary orbit (Struve 1952). This effect was first measured in 1999 with the discovery of the hot Jupiter planet HD 209458 b (Henry et al. 1999, 2000; Charbonneau et al. 2000).

The observed relative decrease in stellar flux during a transit can be approximated as

$$\delta \equiv \frac{\Delta F}{F_\star} = \left(\frac{R_p}{R_\star} \right)^2. \quad (1.3)$$

where $R_p/R_\star$ is the planet–star radius ratio. However, in practice, the photometric light curve produced by a transiting exoplanet also depends on color-dependent stellar limb darkening and can be further complicated by variability produced by stellar activity (e.g., Rosenblatt 1971; Borucki and Summers 1984; Borucki et al. 1985). Equation (1.3) says that if the stellar radius is known through independent means, then measuring the relative photometric drop in brightness during a transit allows one to infer the planet radius. Planetary bulk density can then be calculated if the mass has also been measured via RV detection, in turn providing estimates of bulk interior composition. If multiple transits (or secondary eclipses) of the same planet are detected, then the orbital period

(or a) can also be determined.³ The transit duration will also constrain the planet’s orbital inclination and the mean density of the host star. Lastly, with sufficiently precise photometry, the shape of the transit light curve can also provide information about higher-order effects, such as planet oblateness, circumplanetary rings, and exomoons (Piro 2018b; Piro and Vissapragada 2020; Berardo and de Wit 2022; Harada et al. 2023). Transits also enable measurements of stellar obliquity (via the Rossiter–McLaughlin effect; e.g., Gaudi and Winn 2007; Fabrycky and Winn 2009), planetary atmospheres (via transmission spectroscopy; e.g., Charbonneau et al. 2002), and additional non-transiting planets in the system (via transit timing variations; e.g., Lithwick et al. 2012).

Transit detection is strongly biased toward short-period planets with larger radii compared to their host stars. Under the assumption that planetary orbits are oriented uniformly, it can be shown that the transit probability is $P_{\text{transit}} = R_{\star}/a \propto P^{-2/3}$ for a circular orbit. As a result, 95% of planets detected in transit orbit their host stars with periods shorter than Mercury’s, as shown in Figure 1.2 (Christiansen et al. 2025). While planets orbiting larger host stars are more likely to transit, those planets are actually more difficult to detect due to the $R_{\star}^{-2}$ dependence of the transit depth (Equation (1.3)) and the limited precision of current photometric instruments. Less than 10% of planets detected in transit orbit stars larger than $1.5 R_{\odot}$, and the intrinsic occurrence rate of such planets remains difficult to constrain (e.g., Giacalone and Dressing 2025).

Additionally, care must be taken to vet putative exoplanet transits against an assortment of potential false positives, with common vetting procedures including checking for V-shaped transits, deep secondary eclipses, and/or inconsistencies between odd and even transits. Statistical validation allows one to calculate the Bayesian evidence that a photometric light curve is produced by a transiting planet over alternative astrophysical scenarios (e.g., blended eclipsing binary stars) that can masquerade as true planets (e.g., Torres et al. 2004, 2005; Morton 2012, 2015b; Giacalone et al. 2021; Kunimoto et al. 2025). However, more robust confirmation of transiting planets generally requires independent measurements of the system to verify the planetary nature of the signal. For example, RVs can provide independent evidence for the planetary scenario while providing information about planet mass (and hence bulk density), and high-spatial-resolution imaging (e.g., speckle or adaptive optics imaging) can rule out blended background sources that may produce transit-like signals (e.g., Howell et al. 2011; Dressing et al. 2014; Furlan and Howell 2020; Schlieder et al. 2021; Chontos et al. 2022).

Early transit results relied on ground-based, large-field surveys utilizing modest-aperture telescopes, such as the Hungarian Automated Telescope Network (HATNet; Bakos et al. 2004), the Trans-Atlantic Exoplanet Survey network (TrES; Alonso et al. 2004), the Optical Gravitational Lensing Experiment (OGLE; Konacki et al. 2003), the Wide-Angle Search for Planets (WASP; Pollacco et al. 2006), and the XO project (McCullough et al. 2005). These early transit searches were able to detect a few dozen giant exoplanets on short orbital periods prior to 2008, but were significantly limited due to the long observational baseline and high photometric precision required to detect transiting planets ($\delta \approx 1\%$ for a Jupiter-like planet orbiting a Sun-like star, while $\delta \approx 0.008\%$ for an Earth-like planet). Transits are much easier to detect from space, where atmospheric stability is not a limiting factor. The Convection, Rotation et Transits planétaires (CoRoT)

³Single transit events may also provide some period constraints (e.g., Osborn et al. 2016; Villanueva et al. 2019).

mission became the first space mission whose primary goals included detecting transiting exoplanets with its first light in 2007 (Auvergne et al. 2009). Completing operations in 2013, CoRoT led to the discovery of 35 more transiting planets, including CoRoT-7b, the first super-Earth planet with a measured radius (Queloz et al. 2009; Léger et al. 2009).

To detect even smaller transiting planets, NASA launched the Kepler mission in 2009 with the goal of measuring the frequency of Earth-size planets orbiting Sun-like stars (Borucki et al. 2010). Kepler continuously observed a single 115-square-degree patch of the sky (roughly $10\times$ larger than CoRoT’s field of view) for 4 consecutive years, monitoring over 500,000 stars. To date, Kepler has discovered over 2780 confirmed transiting planets and over 1970 planet candidates (key scientific discoveries from Kepler are discussed further in Section 1.3). In 2013, the second of Kepler’s four reaction wheels malfunctioned, resulting in a loss of pointing stability and the end of its primary mission. However, the spacecraft was repurposed into the K2 mission in 2014 by leveraging solar radiation pressure to counteract the loss of the reaction wheels (Howell et al. 2014). K2 went on to enable 549 more confirmed planet discoveries (and 976 planet candidates) in different parts of the ecliptic plane before running out of fuel in 2018 (e.g., Vanderburg et al. 2016b; Mayo et al. 2018), effectively bridging the gap between the end of the nominal Kepler mission and the start of NASA’s Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al. 2014) which launched the same year.

This staggering sample of precisely measured exoplanets enabled the first robust demographic investigations into planet occurrence rates and system architectures, revealing new information about how, when, and what kind of planets form and evolve around different types of stars (e.g., Borucki et al. 2011; Batalha et al. 2013; Batalha 2014; Ciardi et al. 2015; Winn and Fabrycky 2015; Cloutier and Menou 2020; Dattilo et al. 2023, and many others). A summary of exoplanet occurrence rates from Kepler is included in Section 1.3. Today, the TESS mission continues to make new transiting planet discoveries by scanning nearly the entire sky approximately every 2 years. Unlike Kepler, TESS aims to detect sub-Neptune planets around bright stars that can be easily followed up by ground-based RV observations, enabling precise planetary characterization and target selection for detailed atmospheric spectroscopy with the James Webb Space Telescope (JWST; Gardner et al. 2006; Deming et al. 2009; Kempton et al. 2018). To date, TESS has discovered at least 4780 transiting planet candidates and 885 confirmed planets, of which at least 540 have had RV follow up and 55 have been observed by JWST.

Imaging

While direct imaging is not directly studied in this dissertation, a central motivation for the work presented here is to enable future space-based direct imaging missions that will search for Earth-like exoplanets in the habitable zones of Sun-like stars (discussed further in Section 1.3). Therefore, I briefly summarize the key challenges and scientific insights garnered from previous direct imaging work here.

Exoplanet imaging represents a significant technical challenge because of the very small ratio of planet to stellar brightness and the close angular proximity of planets to their host stars ($\Delta\theta \propto r/d$, where r is the star–planet separation and d is the distance to the system). To an

observer 10 pc away, Earth (Jupiter) would appear only about $0''.1$ ($0''.5$) away from the Sun at maximum elongation. This is often well below typical atmospheric seeing limits for ground-based observations ($\sim 0.3\text{--}1''$) and, even for space-based or wavefront-corrected observations, within the regime where starlight diffraction and speckle noise (defined below) are dominant sources. The diffraction-limited angular resolution is determined by the wavelength of observation, λ , and the telescope aperture diameter, D , as defined by the Rayleigh Criterion: $\theta_{\min} \approx 1.22 \lambda / D$. For a 1 m optical (600 nm) telescope, the diffraction-limited resolution is $\theta_{\min} \approx 0''.15$. This can readily be achieved with the use of adaptive optics (AO) systems, which use active wavefront sensing and deformable mirrors within the optical path to correct for wavefront phase fluctuations in real time (e.g., Babcock 1953; Buffington et al. 1977; Beckers 1993). For a point source such as a star, this will result in an image consisting of a diffraction-limited bright core surrounded by a series of Airy rings containing a few percent of the total flux.

Following wavefront correction, imaging the faint glow of planets around the star usually requires rejecting the diffraction-limited bright stellar core and Airy pattern while preserving any off-axis sources using a coronagraph.⁴ Many coronagraph designs exist today, but in general consist of a focal plane occulting mask, focusing and collimating lenses, and a Lyot stop, which work together to reject the bright on-axis core and surrounding Airy pattern (e.g., Guyon et al. 2006; Mawet et al. 2012; Kenworthy and Haffert 2025). However, even with most of the starlight removed by a coronagraph, the mutual interference of wavefronts creates a random pattern of bright spots (or “speckles”) in the image that dominate over photon noise and any potential signals from planets. This speckle noise must be suppressed or calibrated algorithmically before any companions can be robustly detected. Speckle noise treatments include (not an exhaustive list) interferometric speckle subtraction (e.g., Guyon 2004), angular differential imaging (ADI; e.g., Marois et al. 2006; Lafrenière et al. 2007b), and spectral differential imaging (SDI; e.g., Racine et al. 1999; Vigan et al. 2010).

Aside from the close angular proximity of planets to their host stars, the very small ratio of planet to stellar brightness presents another challenge. For wavelength λ , the total planet-to-star flux ratio can be written

$$\frac{F_p(\alpha, \lambda, t)}{F_\star(\lambda)} = A_g(\lambda) \phi(\alpha) \left(\frac{R_p}{r(\alpha)} \right)^2 + \frac{F_{\text{emit}}(\lambda, t, M_p)}{F_\star(\lambda)}, \quad (1.4)$$

where $A_g(\lambda)$ is the geometric albedo, $\phi(\alpha)$ is a function that varies between 0 and 1 depending on phase angle α , and $r(\alpha)$ is the instantaneous star–planet separation. The first term accounts for reflected starlight whereas the second term accounts for thermal emission by the planet, which in general depends on the planet mass and decreases with system age, t , as the planet’s heat of formation is gradually lost to radiative cooling⁵ (e.g., Burrows et al. 1997; Baraffe et al. 2003; Burrows et al. 2004; Linder et al. 2019). The reflected-light term is very small ($\sim 10^{-9}$ for the

⁴The first coronagraphs were used to observe the solar corona without an eclipse, hence the name (Hale 1895; Lyot 1939).

⁵The thermal emission is also affected by factors such as atmospheric metallicity, cloud or haze properties, radiogenic decay, and tidal heating (e.g., Leconte et al. 2010; Mordasini et al. 2012; Malik et al. 2019).

Jupiter–Sun system and $\sim 10^{-10}$ for the Earth–Sun system in the optical), but the thermal emission term can dominate for giant planets in young systems, which remain hot from their formation (e.g., $\sim 10^{-5}$ at $\sim 5 \mu\text{m}$ for a 100 Myr, 1 M_{J} planet at 4 au; Burrows et al. 2004). As a result, direct imaging searches have historically been biased toward detecting young, giant planets at infrared (IR) wavelengths with large angular separations their host stars. To date, direct imaging has detected 47 sub-stellar objects with $M_{\text{p}} < 13 M_{\text{J}}$ (approximately the deuterium burning limit), whose median age is about 15 Myr (Christiansen et al. 2025).

Numerous direct imaging surveys have detected massive, young, self-luminous and wide-orbiting planets, while ongoing and future imaging surveys aim to detect and spectroscopically characterize smaller, older, and closer-in planets. For example, the Gemini Deep Planet Survey conducted a NIR AO search for giant planets and brown dwarfs around 85 nearby young stars, determining 95% credible upper limits on the fraction of stars with at least one planet of mass 0.5–13 M_{J} to be 0.28 for the range 10–25 au (Lafrenière et al. 2007a). They found that the percentage of stars with at least one planet of that size decreases to 13% between 25–50 au, and further decreases to 9.3% at 50–250 au. Subsequent work with Gemini, the Gemini Planet Imager (GPI) Exoplanet Survey (GPIS; Macintosh et al. 2015), leveraged a much larger sample of 300 stars and improved sensitivity to show that the integrated occurrence rate of planets between 5–13 M_{J} and 10–100 au is $9^{+5}_{-4}\%$, and that stars larger than 1.5 $M_{\odot}$ are more likely to host giant planets (2–13 M_{J}) between 3–100 au with 99.92% confidence (Nielsen et al. 2019). In another survey of approximately 500 stars, the Spectro-Polarimetric High-contrast Exoplanet REsearch (SPHERE) INfrared Exoplanet (SHINE) project (Desidera et al. 2021; Langlois et al. 2021) reported an occurrence rate of systems with at least one 5–13 M_{J} companion between 3–100 au of $8.6^{+7.3}_{-4.5}\%$, consistent with Nielsen et al. (2019), and found that the frequency of substellar companions is significantly higher around BA stars than around FGK and M stars (Vigan et al. 2021). These imaging survey results are consistent with a peak in occurrence of giant planets between ~ 1 and 10 au, and help to constrain how different planet formation pathways lead to the observed distribution of giant substellar companions in the ~ 1 –300 au regime. For example, based on the SHINE results, Vigan et al. (2021) suggest that planet-like (i.e., core-accretion) formation likely dominates for 1–75 M_{J} companions around BA stars, while star-like (i.e., direct gravitational collapse) formation dominates for brown dwarf companions around M dwarfs. A combination of both binary star-like and planet-like formation mechanisms are likely necessary to explain observations of FGK stars. From space, both the Hubble Space Telescope (HST) and JWST have also contributed to direct imaging discoveries and improved our ability to characterize the atmospheres of imaged companions by giving us access to ultraviolet (UV) and IR wavelengths not accessible from the ground (e.g., Kalas et al. 2005, 2008, 2015; Carter et al. 2021; Lagrange et al. 2025).

1.2 Planetary Habitability

Despite thousands of exoplanet discoveries, no unambiguously habitable exoplanets have been detected and their formation processes are not fully understood. Current assumptions regarding the habitability of exoplanets are largely based on our understanding of life on Earth. Namely,

the consensus that carbon-based life on Earth requires water has motivated searches for habitable planets to focus on identifying environments that can sustain stable liquid water over long ($\sim$ Gyr) timescales. The presence of liquid water would also imply atmospheric pressures and temperatures that are suitable for biological reactions to occur. As a result, the circumstellar habitable zone (HZ) has long been defined as the range of star–planet distances where conditions are neither too hot nor too cold to allow stable liquid water to exist on a rocky planet’s surface (e.g., Huang 1959, 1960; Dole 1964; Hart 1979). While in most cases, the temperature of an exoplanet cannot be measured directly, a first-order estimate can be calculated based on the luminosity of the host star ($L_\star$) and the star–planet distance for a circular orbit (a):

$$T_{\text{eq}} = \left[\frac{L_\star(1 - \alpha_B)}{16\sigma\pi a^2} \right]^{1/4} \quad (1.5)$$

where α_B is the Bond albedo (which is often unknown for exoplanets) and σ is the Stefan–Boltzmann constant. Equation (1.5), known as the equilibrium temperature, is the temperature of an isothermal sphere with the same bond albedo and semimajor axis as the planet.

However, the boundaries of the HZ are also controlled by factors such as the planet’s atmospheric composition and circulation, tidal or radiogenic heating, orbital eccentricity, and obliquity (e.g., Barnes et al. 2008; Spiegel et al. 2009; Dressing et al. 2010; Heller et al. 2011; Wolf and Toon 2013). In particular, the presence of greenhouse gases (e.g., H_2O , CO_2 , CH_4) in the planetary atmosphere can significantly increase the surface temperature from Equation (1.5). As a consequence, the inner edge of the HZ for Earth-like planets orbiting Sun-like stars is usually defined by a runaway greenhouse effect resulting in water loss due to a CO_2 -rich atmosphere (Kasting 1988). At the other extreme, the outer limit of the HZ is determined by the maximum greenhouse effect that can be achieved before the onset of CO_2 condensation, resulting in increased planetary albedo and runaway glaciation. Physical 1D climate models have predicted precise HZ limits for water loss (inner) and maximum greenhouse effect (outer) assuming a planetary atmosphere consisting of H_2O , CO_2 , and N_2 (Kasting et al. 1993). More recent radiative–convective equilibrium modeling with updated molecular absorption coefficients have predicted these limits to be 0.99–1.70 au for a Sun-like star, and extended this work to predict HZ limits around other FGKM stars with effective temperatures from 2600–7200 K and planets with masses 0.1–5 $M_\oplus$ (Kopparapu et al. 2013, 2014).

Additional research has continued to refine the HZ boundaries with considerations such as 3D effects, cloud cover, climate feedback (e.g., the carbonate–silicate cycle), atmospheric pressure, outgassing, and land/ocean fraction (e.g., Kasting 1988; Spiegel et al. 2008; Leconte et al. 2013a,b; Seager et al. 2013; Shields et al. 2013, and many others). Other, less conservative limits for the circumstellar HZ (e.g., Kasting et al. 1993; Kopparapu et al. 2013) are based on the inference that liquid water has been absent from the surface of Venus for at least 1 Gyr (the “recent Venus” limit; Solomon and Head 1991) and that liquid water was present on the surface of Mars about 3.8 Gya (the “early Mars” limit; Pollack et al. 1987). The boundaries of the HZ as defined by Kopparapu et al. (2013) are shown in Figure 1.3 along with known confirmed exoplanets whose orbits at least partially intersect with the optimistic HZ.

While the circumstellar HZ is useful as an initial framework for constraining planetary habitability, the likelihood that any given planet is actually habitable (or inhabited) in reality depends on

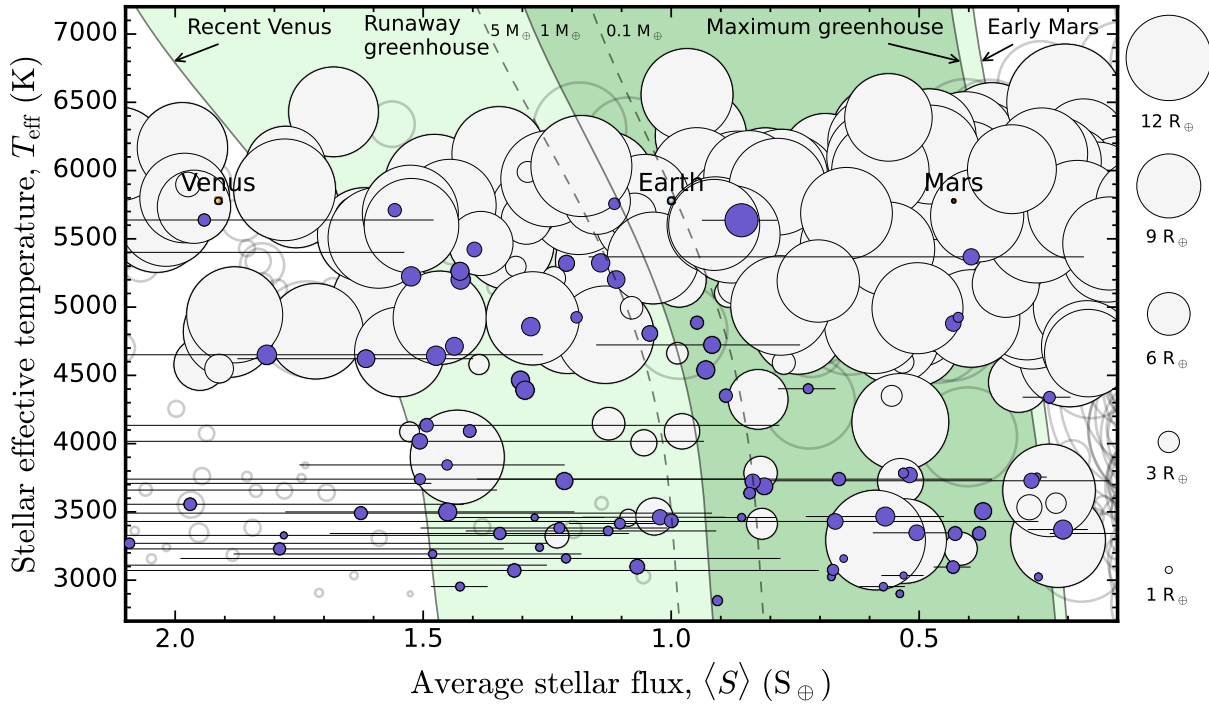


Figure 1.3: Confirmed planets in the habitable zone. Planets whose mass or radius are known to 25% precision or better are shown by filled circles, with circle size corresponding to planet radius. The purple circles show planets that are likely to be rocky ($R_p < 2.0 R_\oplus$ or $M_p < 8.0 M_\oplus$) and the horizontal bars show the minimum and maximum instellation values for planets on eccentric orbits. The plotted values represent the orbit-averaged instellation flux $\langle S \rangle$ for a given orbit defined by a and e around a host star with temperature T_{eff} , where $\langle S \rangle \propto a^{-2}(1 - e^2)^{-1/2}T_{\text{eff}}^4$. The conservative (dark green) and optimistic (light green) HZ limit definitions are taken from Kopparapu et al. (2014). The Solar System planets Venus, Earth, and Mars are shown for reference. *Data were obtained from the NASA Exoplanet Archive (Christiansen et al. 2025), accessed on 30 April 2026.*

many interconnected factors. The diagram in Figure 1.4 (reproduced from Meadows and Barnes 2018) highlights several dozen possible factors affecting habitability ranging from stellar effects (e.g., spectral energy distribution, composition and structure, galactic location) to system-wide effects (e.g., sibling planets, orbital evolution) to planetary effects (e.g., interior, atmosphere, orbital dynamics, surface conditions). Most of the work presented in this dissertation focuses on the former two: stellar effects (Chapter 3) and the influence of other planets within the system (Chapters 2 and 4). These topics are discussed in greater detail in those chapters, but I summarize the key points here. For comprehensive discussions of planetary habitability, please refer to Kaltenegger et al. (2007), Zahnle et al. (2007), Seager (2013), and Meadows and Barnes (2018).

Stellar Effects

“Know thy star; know thy planet” is a common mantra within the exoplanet community because uncertainties in host star properties propagate directly to the inferred properties of exoplanets (e.g., R_p , M_p , T_{eq}). It follows that robust knowledge of the host star is a prerequisite for making accurate predictions or inferences about habitability (see Chapter 3). For example, although the planetary equilibrium temperature in Equation (1.5) is written in terms of the star’s bolometric luminosity, the way that the star’s energy output is distributed as a function of wavelength (i.e., the spectral energy distribution, or SED) is also an important factor for habitability due to the wavelength-dependent absorption cross sections of greenhouse gases like H_2O and CO_2 . Kopparapu et al. (2013) used a grid of BT-Settl stellar atmosphere models (Allard et al. 2003, 2012) as input spectra for their HZ boundary calculations. Normalized to the same bolometric luminosity, the different input spectra caused the HZ boundaries to shift inward for hotter stars (F dwarfs) compared to cooler stars (M dwarfs) due to (1) the greater amount of atmospheric Rayleigh scattering ($\sigma_{\text{Rayleigh}} \propto \lambda^{-4}$) experienced by planets orbiting hotter stars, whose Wien peak is bluer than cooler stars; and (2) the weaker absorption cross sections of H_2O and CO_2 at bluer wavelengths, again closer to the Wien peak for hotter stars.

The UV portion of the stellar SED ($\sim 200\text{--}300$ nm) is of particular interest for habitability for numerous reasons. Exposure to excess UV radiation can destroy or damage DNA and other organic compounds necessary for life, but it is also believed that UV radiation could have been an important energy source underlying biochemical synthesis early in Earth’s history (e.g., Sagan 1973; Buccino et al. 2003, 2006, 2007; Sato et al. 2014; Ranjan et al. 2017). UV radiation can also drive photochemistry in rocky planet atmospheres, which can dramatically alter atmospheric structure and surface UV environments over geologic timescales, especially by modifying concentrations of O_3 and photochemical hazes (e.g., Segura et al. 2003; Kaltenegger et al. 2007; Rugheimer et al. 2015a,b). Therefore, observational programs have recently sought to characterize the UV environments of planet-hosting stars. For example, the Measurements of the Ultraviolet Spectral Characteristics of Low-mass Exoplanetary Systems (MUSCLES) survey was a panchromatic (X-ray to mid-IR) study of the SEDs of 11 K- and M-type stars with confirmed planets (France et al. 2016; Youngblood et al. 2016). In addition to using ground-based observations, the MUSCLES program leveraged HST and the Chandra and XMM-Newton X-ray observatories to measure the $Ly\alpha$, extreme-UV, and X-ray emission of their target stars, allowing them to reconstruct the full $5\text{ \AA--}5.5\text{ }\mu\text{m}$ SEDs (Lloyd et al. 2016).

It is important to note that the energy output of stars also evolves over time, either as cyclical variability (e.g., stellar pulsations or rotation) or secular evolution as stellar nucleosynthesis depletes hydrogen fuel in the core. For pulsating or rotating stars, recent investigations suggest that variability on timescales of 1–10 days and amplitudes up to several thousand ppm has negligible influence on the equilibrium temperature and H_2O retention of planets within the HZ detected by TESS, yet additional work is necessary to understand the effects of longer-period variability (Fetherolf et al. 2023, 2026). Rapid rotation in F- or A-type stars can dramatically change the stellar luminosity and SED by increasing oblateness and creating equator–pole temperature gradients, which in turn influence a planet’s irradiation, shift the HZ closer to the star, and suppress

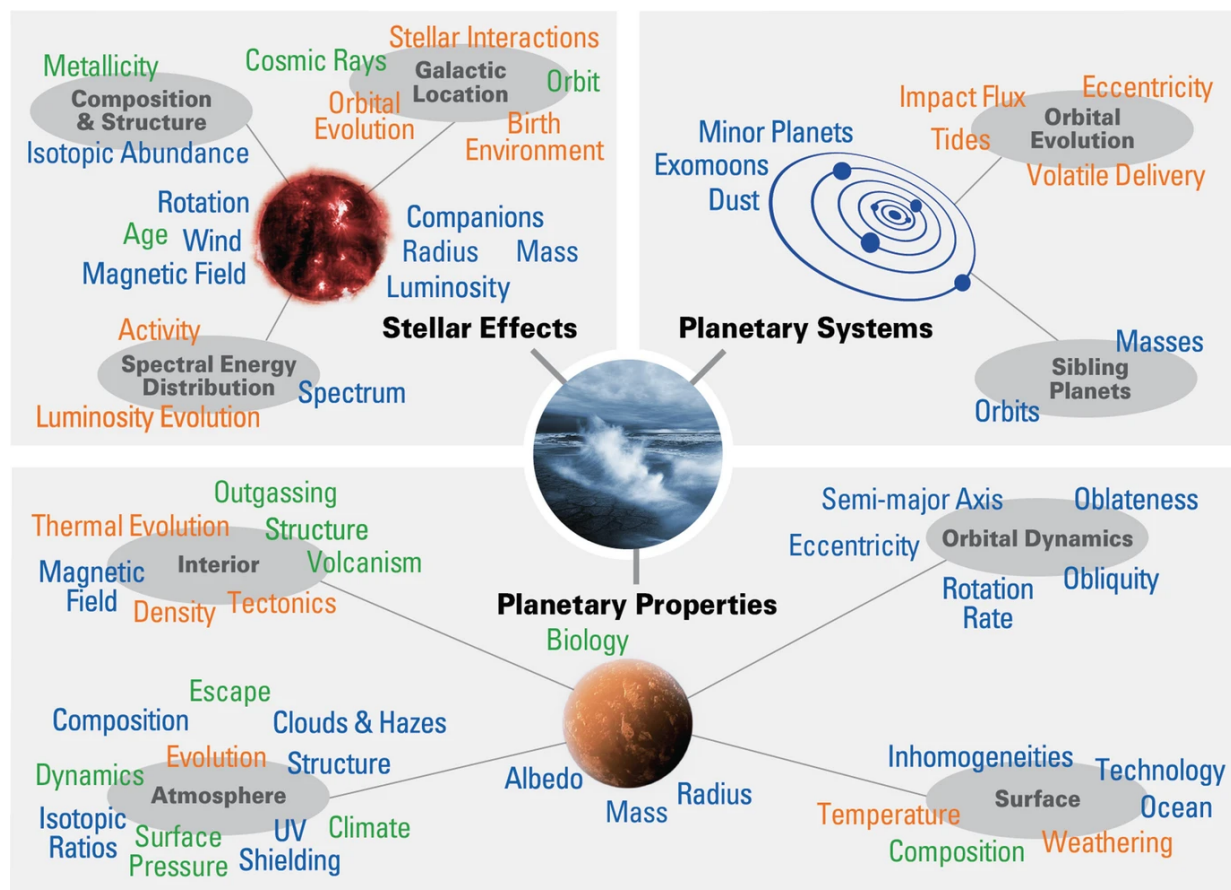


Figure 1.4: Factors affecting habitability. This diagram shows currently understood planetary, stellar, and planetary system properties that may impact planetary habitability. The larger the number of these factors that can be determined for a given habitable zone candidate, the more robust our assessment of habitability will be. Font color denotes characteristics that could be observed directly with sufficiently powerful telescopes (blue), those that require modeling interpretation, possibly constrained by observations (green), and the properties or processes that are accessible primarily through theoretical modeling (orange). *Figure and caption adapted from Meadows and Barnes (2018).*

UV emission (Ahlers et al. 2022). However, more massive stars (O, B, and A spectral types) may be less promising for habitability due to their shorter main-sequence lifetimes (only millions to a few billion years, opposed to ~ 10 Gyr for G2V star like the Sun). For stars whose variability stems from stellar activity (e.g., rotationally modulated starspots), the associated increase in stellar flare rates can irradiate HZ planets with large amounts of UV and X-ray flux, resulting in changes to atmospheric chemistry and surface UV environments, especially for planets orbiting M and K dwarfs (e.g., Scalo et al. 2007; Gallet et al. 2017; Günther et al. 2020; Ridgway et al. 2023). Additionally, secular stellar evolution will profoundly affect planetary habitability as stars evolve from the pre-main-sequence stage (which can last up to ~ 1 Gyr for low-mass stars) to the

main sequence, and eventually deplete their core hydrogen to become red giants or super-giants.⁶ The continuously habitable zone (CHZ) accounts for changes in stellar luminosity and spectral type with age, and defines the range of orbital distances over which liquid H₂O could have existed continuously on timescales conducive to the evolution of life (e.g., Hart 1978, 1979; Kasting and Catling 2003; Underwood et al. 2003). For the Sun, the CHZ over the past 4 Gyr is estimated to lie between 0.95–1.15 au. Lastly, massive stars that evolve through the red giant branch or asymptotic giant branch post-main-sequence stages will undergo substantial envelope mass loss, leading to secular orbital migration and driving stellar winds that can erode planetary atmospheres and reduce habitability (e.g., Ramirez and Kaltenegger 2016).

Planetary Properties

Here on Earth, our planet’s interior structure, surface, atmosphere, oceans, and biosphere form a complex integrated system that evolves over time (see the bottom panel of Figure 1.4). A comprehensive understanding of how each of these factors affects one another is the subject of geoscience and largely beyond the scope of this work. Below, I discuss a few examples of how planetary properties may be linked to habitability based on observations from the Solar System, but it should be emphasized that the interplay between these factors and habitability is still not completely understood on Earth, let alone other planets.

From seismological data, we know that the Earth’s interior consists of a solid Fe–Ni inner core surrounded by a fluid metallic outer core contained within a radius of $\sim 0.5 R_{\oplus}$. A viscous mantle surrounds the core (composed mainly of O-, Mg-, and Si-rich minerals), followed by the asthenosphere, lithosphere, and crust (the uppermost ~ 6 –35 km). In these upper layers, processes such as volcanism and plate tectonics help regulate greenhouse gas concentrations in the atmosphere through outgassing and the carbonate–silicate cycle (weathering), impacting long-term climate evolution (e.g., Lenardic et al. 2016). However, plate tectonics are absent from present-day Venus (possibly due to a higher viscosity mantle) which could have been a contributing factor to Venus’ runaway greenhouse and subsequent water loss (Nimmo and McKenzie 1998). As one example, the ratio of Mg to Si is predicted to significantly influence rocky planet mineralogy, causing planets with low Mg/Si to have higher mantle viscosity and therefore forcing them to cool more slowly after formation and lose their volatiles more quickly (Spaargaren et al. 2020). On the other hand, low Mg/Si is associated with a more rigid mantle due to its influence on mineralogical condensation sequences, implying that higher Mg/Si may be required for sustained lithospheric processes like volcanism and plate tectonics that can help stabilize global climate (e.g., Jorge et al. 2022; Spaargaren et al. 2023).

As one additional example, the element phosphorus is of particular importance to biogeochemistry because it is the limiting nutrient for biochemical reactions necessary for life, and an essential component of DNA, RNA, and ATP (adenosine triphosphate), which are the complex organic molecules responsible for encoding genes, instructing cellular functions, and transferring

⁶Habitability of planets orbiting stellar remnants such as white dwarfs is not discussed here (see, e.g., Vanderburg et al. 2025).

energy between cells (Schlesinger and Bernhardt 2013). However, the distribution and abundance of phosphorus in the Milky Way is poorly understood due to its faint NIR absorption signature in stellar spectra that make it challenging to measure (e.g., Hinkel et al. 2014, 2020). This is addressed further in Chapter 3. Again, I emphasize that is not a comprehensive discussion of the many potentially important geochemical considerations for habitability (see, e.g., Meadows and Barnes 2018 for a more comprehensive review).

While planetary bulk densities calculated from mass and radius measurements can loosely (due to degeneracies) constrain a planet’s composition, direct observations of rocky planet surfaces and interiors are currently beyond our reach. However, observations of host star composition can provide clues to rocky planet interiors, surfaces, and atmospheres that may be important for habitability (Unterborn et al. 2023). Because stars and planets form from a common molecular cloud and protoplanetary disk, their chemical compositions are fundamentally connected (although the details of how the protoplanetary material is partitioned between and within the planets and host star remain an active area of research; e.g., Gáspár et al. 2016; Santos et al. 2017; Bitsch and Battistini 2020; Schulze et al. 2021). Nonetheless, stellar abundances measurements of rocky planet building blocks (e.g., Si, Mg, Al, Fe, and Ni) and the fundamental ingredients for life on Earth (e.g., C, N, O, P, and S) can provide useful constraints on plausible rocky world geophysical scenarios and potential habitability based on planet devolatilization models (e.g., Hinkel and Unterborn 2018; Plotnykov and Valencia 2020; Adibekyan et al. 2021; Wang et al. 2022; Cabral et al. 2023).

Planetary Systems

Planetary system context, referring to orbital evolution and the masses and orbits of sibling planets or moons, is also a critical factor linked to planetary habitability. For example, Earth’s climate has varied substantially over ~ 10 – 100 kyr timescales due to the combined effects of changing obliquity, orbital eccentricity, and precession (i.e., the Milankovitch cycles; e.g., Milanković 1941; Berger 1980; Bennett 1990; Laskar et al. 2004), and these processes generalize to potentially habitable planets in other systems (Spiegel et al. 2010; Rosengren and Scheeres 2014; Way and Georgakarakos 2017). Planetary obliquity and orbital eccentricity in part control seasonal climate variations, but in extreme cases can lead to transient or sustained loss of habitability (e.g., planets in highly eccentric orbits spend the majority of time far away from the host star where global “snowball” states could take hold). The limits of obliquity and eccentricity that can sustain habitable climates have been shown to be surprisingly broad, at least for Sun-like stars, with thermal inertia playing an especially important role on planets with even high land/ocean fractions. For example, it has been shown that planets could have eccentricities exceeding ~ 0.7 and semimajor axes between ~ 1.1 – 1.4 au without undergoing a snowball transition (e.g., Williams and Pollard 2002; Spiegel et al. 2009; Dressing et al. 2010).

Additional dynamical effects, namely tidal evolution, are expected to be particularly relevant for rocky planets orbiting low-mass M dwarfs whose HZs are much closer in (e.g., Barnes et al. 2008; Heller et al. 2011). For example, at small orbital separations the gravitational differential across the planet raises a tidal bulge ($F_{\text{tide}} \propto R_p r^{-3}$ where r is the star–planet separation) that is misaligned from the star–planet line of centers due to internal friction, which then feels a torque

from the host star that acts to decrease the planet’s rotation rate and eccentricity. Eventually, this can lead to a tidally locked state in which the planet has a permanent day side and a permanent night side, leading to extreme day–night temperature gradients that can cause low-pressure atmospheres ($\lesssim 1000$ hPa) to collapse or “freeze out” on the much colder night side (e.g., Joshi et al. 1997).

Tidal evolution can also have a significant impact on the orbital stability and potential habitability of moons (or exomoons), adding yet another layer of complexity. For example, for a moon-hosting planet, tides could help stabilize long-term climate by damping obliquity oscillations (Laskar et al. 1993; Lissauer et al. 2012) or providing additional internal heat to the planet through tidal dissipation (e.g., Piro 2018a). Moons that are themselves potentially habitable could similarly be heated through tidal dissipation (e.g., Carr et al. 1998; Roberts and Nimmo 2008; Heller and Barnes 2013), while in extreme cases tidal evolution could lead to a moon’s gravitational escape or collision with its host planet. As I discuss further in Chapter 2, this is an especially relevant consideration for moons orbiting giant planets in the circumstellar HZ, such as HIP 41378 f (e.g., Heller 2014; Teachey et al. 2018; Kipping et al. 2022).

Finally, the semimajor axes, eccentricities, and mutual inclinations of sibling planets within the system may play an important role in sculpting planetary system architectures and transporting volatile material from beyond the H_2O ice line to the HZ (e.g., Raymond et al. 2004, 2008; Kane and Wittenmyer 2024). Additionally, as is relevant for Chapters 4 and 5, the properties of sibling planets determine whether rocky planets in the HZ could have stable orbits (e.g., Kane 2015; Kane and Blunt 2019). Though giant planets with HZ crossing orbits will have a significant effect on the dynamical stability of HZ Earth analogs, even sub-Neptune planets in proximity to the HZ can significantly limit the fraction of the HZ that is dynamically viable (Kane and Fetherolf 2023). Past episodes of significant planetary migration (e.g., in hot Jupiter systems) could also preclude any extant HZ planets today due to planet–planet scattering (Ford and Rasio 2008; Chatterjee et al. 2008) or von Zeipel–Kozai–Lidov (ZKL) oscillations (Kozai 1962; Lidov 1962; Fabrycky and Tremaine 2007). While systems with such extreme migration histories appear to be uncommon (~ 1 hot Jupiter per 100 stars; Wright et al. 2012; Wittenmyer et al. 2020), the occurrence rate of cold Jupiters is significantly higher and appears to peak between 1–10 au where dynamical interactions with HZ planets may be important. Empirical transit and RV estimates of the cold Jupiter occurrence rate include $26.6^{+7.5}_{-5.4}$ giant companions (~ 0.1 – $20 M_J$) between 0.1–100 au per 100 stars (Fernandes et al. 2019) and $14.1^{+2.0}_{-1.8}$ giant companions between 2–8 au per 100 stars (Fulton et al. 2021). Although these occurrence rate estimates are still relatively low, the limited amount of observational data we currently have introduces significant uncertainties in the results, especially for lower-mass planets ($\lesssim 0.1 M_J$) whose demographics at $P \gtrsim 100$ days are much less constrained. It is therefore prudent to characterize the orbits and masses of non-Earth-like planets orbiting near the HZ for future exoEarth searches.

1.3 The Search for ExoEarths

Kepler Planet Occurrence Rates

One of the most exciting results to come out of space-based transit surveys (particularly Kepler) has been that small planets are common in the Milky Way (e.g., Howard et al. 2012; Dressing and Charbonneau 2013; Fressin et al. 2013). In particular, Kepler enabled statistically robust estimates of the intrinsic occurrence rate of Earth-size planets around Sun-like stars, which is symbolized by $\eta_{\oplus}$ (“Eta Earth”) and calculated as the average number of Earth-size planets per star within a given period range for a given stellar type.⁷ Importantly, reliable measurements of $\eta_{\oplus}$ must account for search completeness, detection efficiency, random and systematic errors, false-positives, and the geometric transit probability, and depend heavily on accurate stellar properties (Gaidos and Mann 2013; Dressing and Charbonneau 2013; Christiansen et al. 2013, 2015, 2016). Due to differing treatments of these factors (and the assumed definition of $\eta_{\oplus}$), estimates of $\eta_{\oplus}$ have varied substantially in the literature.

In general, Kepler revealed that, for $P < 50$ days, the average number of planets per star is ~ 0.2 for radii between $1\text{--}2 R_{\oplus}$ and ~ 0.4 for radii $> 1 R_{\oplus}$ (Dong and Zhu 2013; Petigura et al. 2013a,b). For stars cooler than 4000 K, Dressing and Charbonneau (2013) found that the occurrence rate of $0.5\text{--}4 R_{\oplus}$ planets in the Kepler sample with orbital periods shorter than 50 days is $0.90^{+0.04}_{-0.03}$ planets per star. Dressing and Charbonneau (2013) also found that the occurrence of Earth-size ($0.5\text{--}1.4 R_{\oplus}$) planets remained constant across the temperature range of their sample at $0.51^{+0.06}_{-0.05}$ planets per star, but the occurrence of $1.4\text{--}4 R_{\oplus}$ planets decreases significantly at cooler temperatures. For G and K dwarfs, Burke et al. (2015) estimated $\eta_{\oplus} \sim 0.1$ and an occurrence rate of 0.77 planets per star for $0.75 R_{\oplus} < R_p < 2.5 R_{\oplus}$ with periods between 50–300 days. Gaidos (2013) gave a much higher estimate of $\eta_{\oplus} = 0.46^{+0.18}_{-0.15}$ for Kepler dwarf stars, with a 95% confidence interval of 0.31–0.64 Earth-like planets per star. Additionally, Fressin et al. (2013) estimated that $16.5 \pm 3.6\%$ of FGK dwarfs have at least one planet between $0.8\text{--}1.25 R_{\oplus}$ with $P < 85$ days, and Petigura et al. (2013a) found that 22% of Sun-like stars could harbor Earth-size planets orbiting in their HZs and $11 \pm 4\%$ of Sun-like stars harbor an Earth-size planet receiving 1–4 times the stellar irradiance received by Earth. While there yet to be a clear consensus on $\eta_{\oplus}$, small rocky planets that could potentially resemble Earth do appear to be a common outcome of planet formation.

Although Kepler set a new standard in our understanding of how *common* potentially Earth-like planets are, only a relatively small subset of those planets have been thoroughly characterized and no conclusive evidence of habitability has yet been obtained. Only $\sim 11\%$ of confirmed Kepler planets have measured masses or mass limits (Christiansen et al. 2025) in large part due to low SNR resulting from a combination of faint host stars (an average Kepler planet host star has $V = 14.5$ and $K_s = 12.6$) and the low-amplitude RV signals produced by small planets. Nonetheless, since the discovery of Kepler-22 b (Borucki et al. 2012), a growing number of small HZ planets have

⁷It is worth mentioning that there is no precise and universally agreed upon definition for $\eta_{\oplus}$, as opinions differ on what qualifies exactly as “Sun-like” or “Earth-size” and which HZ boundaries to adopt for $\ln P$ binning. For example, Borucki et al. (2011) assumed planets with $R_p < 1.25 R_{\oplus}$ qualified as Earth-size, while Kopparapu et al. (2013) adopted limits of $0.5\text{--}1.4 R_{\oplus}$.

been announced resulting from both transit and RV searches. Currently, 89 confirmed planets on the NASA Exoplanet Archive⁸ orbit completely or partially in the HZ and have $R_p < 2.0 R_\oplus$ or $M_p < 8.0 M_\oplus$ measured to at least 25% precision (shown in Figure 1.3). Of those planets, only 5 have both radius *and* mass measurements with better than 25% precision⁹ (LHS 1140 b and TRAPPIST-1 d, e, f, and g; Dittmann et al. 2017; Gillon et al. 2016; Gillon et al. 2017b), emphasizing that we still have much to learn about the properties of potentially rocky planets in order to accurately assess their habitability. Even so, extensive work has been done to model the HZs of these systems to better understand the possible climates of their HZ planets (e.g., Jones and Sleep 2010; Cantrell et al. 2013; Kane 2014), and multiple catalogs of potentially habitable planets have been released to the community for further study, including the Habitable Worlds Catalog,¹⁰ among others (e.g., see Kane and Gelino 2012; Hill et al. 2023; Bohl et al. 2026). As TESS continues to make new discoveries of planets around bright stars, dedicated EPRV surveys and transit follow up will provide increasingly precise mass measurements of small planets that will push the limits of our ability to characterize HZ rocky planets, model their atmospheres and interiors, and constrain their habitability (e.g., Gilbert et al. 2020; Lillo-Box et al. 2020; Cifuentes et al. 2020; Brewer et al. 2020; Gupta et al. 2025).

The M Dwarf Advantage

So far, the only known habitable planet (Earth) orbits a main-sequence G-type star (the Sun). However, although we ultimately wish to constrain the occurrence of potentially habitable planets that are Earth-like in terms of both the planet and host star, the search for exoEarths until now has focused largely on rocky planets orbiting stars much smaller than the Sun. Specifically, M dwarfs have been of particular interest in the search for Earth-like planets because they are not only the most common type of star in the galaxy, but also the best suited for characterizing HZ terrestrial planets in several ways. The advantages of studying M dwarfs (especially late M dwarfs) include:

1. *Closer-in habitable zones.* The orbital separation of the HZ scales approximately at $r_{\text{HZ}} \propto L_\star^{1/2}$. M dwarfs, which can be hundreds of times less luminous than the Sun, therefore have HZs that are significantly closer in. Any planets orbiting in this range will have much shorter orbital periods than planets in the HZ of brighter, hotter stars increasing the likelihood of detection and boosting SNR by a factor of $\sqrt{N}$.
2. *Larger $R_p/R_\star$ and transit probability.* The transit depth scales as $\delta \propto R_\star^{-2}$, so for a fixed planet radius the transit depth will be significantly larger for an M dwarf than it would be for a larger, hotter star, resulting in higher SNR. Additionally, the geometric transit probability

⁸<https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PSCompPars>

⁹In most cases, either mass or radius is inferred from the other through interior structure and evolution modeling, requiring assumptions to be made regarding composition, mass fractions, and equations of state (e.g., Dorn et al. 2015; Wolfgang et al. 2016; Chen and Kipping 2017; Müller et al. 2024).

¹⁰<https://phl.upr.edu/hwc>

scales as $P_{\text{transit}} \propto R_*$, so we are more likely to observe transit events around smaller stars than larger ones.

3. *Larger RV semi-amplitude.* For RV surveys and follow-up observations, the RV semi-amplitude scales as $K \propto M_*^{-2/3}$, meaning that for a fixed planet mass the strength of the RV signal will be higher for lower-mass stars like M dwarfs than it would be for more massive stars. Again, this increases the SNR for low-mass rocky planets.

These advantages have made M dwarfs fruitful laboratories for many studies of rocky exoplanets. Small planets are extremely common around these small stars with a Kepler occurrence rate of 2.2 ± 0.3 planets per M dwarf for planets with $1\text{--}4 R_{\oplus}$ and P between 1.5–180 days (Gaidos et al. 2016), and these planets very often exist in compact ($P < 10$ days) multi-planet systems (e.g., $21 \pm 6\%$ of mid-M dwarfs, Muirhead et al. 2015). This abundance of rocky planets in tightly-packed systems and their host star properties, orbital architectures, mutual inclinations, and mean-motion resonances point to highly efficient accretion of protoplanetary disk material by mid-M dwarf protoplanets (e.g., Fabrycky et al. 2014; Millholland et al. 2017; Weiss et al. 2018). Within the HZ of dwarf stars with temperatures below 4000 K, Dressing and Charbonneau (2013) estimated that the mean number of Earth-size planets is $\eta_{\oplus} = 0.15^{+0.13}_{-0.06}$ per star, with a 95% confidence lower limit of 0.04 Earth-size planets per cool-star HZ. Using the full four-year Kepler data set, all publicly available follow-up data, and transit injection–recovery test to measure search completeness, Dressing and Charbonneau (2015) improved the estimate of the occurrence rate of small planets orbiting small stars. For $P < 50$ days, Dressing and Charbonneau (2015) found $0.56^{+0.06}_{-0.05}$ Earth-size planets ($1\text{--}1.5 R_{\oplus}$) and $0.46^{+0.07}_{-0.05}$ super-Earths ($1.5\text{--}2 R_{\oplus}$) per M dwarf, and within the conservative HZ they estimated an occurrence rate of $0.16^{+0.17}_{-0.07}$ Earth-size planets and $0.12^{+0.10}_{-0.05}$ super-Earths per M dwarf.

Although rocky planets orbiting M dwarfs appear to be quite common, the likelihood that these planets are actually habitable remains a very area of active research. A primary concern is the long (~ 1 Gyr) pre-main-sequence lifetime of the lowest-mass stars, during which any rocky (proto)planets would be exposed to significant X-ray and extreme ultraviolet (XUV) radiation and flaring events (e.g., Luger et al. 2015). Given a high enough historic XUV fluence for a given planet mass, this prolonged exposure to ionizing photons could pose a threat to long-term atmospheric stability and water retention (an idea coined the “cosmic shoreline”; e.g., Zahnle and Catling 2017; Pass et al. 2025). New NIR spectroscopic observations with JWST have recently begun probing suitable rocky planet targets orbiting M dwarfs to test whether they can retain or replenish their secondary atmospheres (e.g., the JWST Rocky Worlds DDT Program¹¹). For example, recent secondary eclipse emission spectroscopy observations of the M-dwarf planet GJ 3929 b are consistent with a bare-rock surface (Xue et al. 2025), and transmission spectroscopy of the super-Earth GJ 486 b have thus far not been able to distinguish between a water-rich atmosphere scenario and stellar contamination due to the presence of H₂O molecules in cool unocculted starspots (Moran et al. 2023). For these reasons, the exoplanet community continues to advance toward the long-

¹¹<https://rockyworlds.stsci.edu>

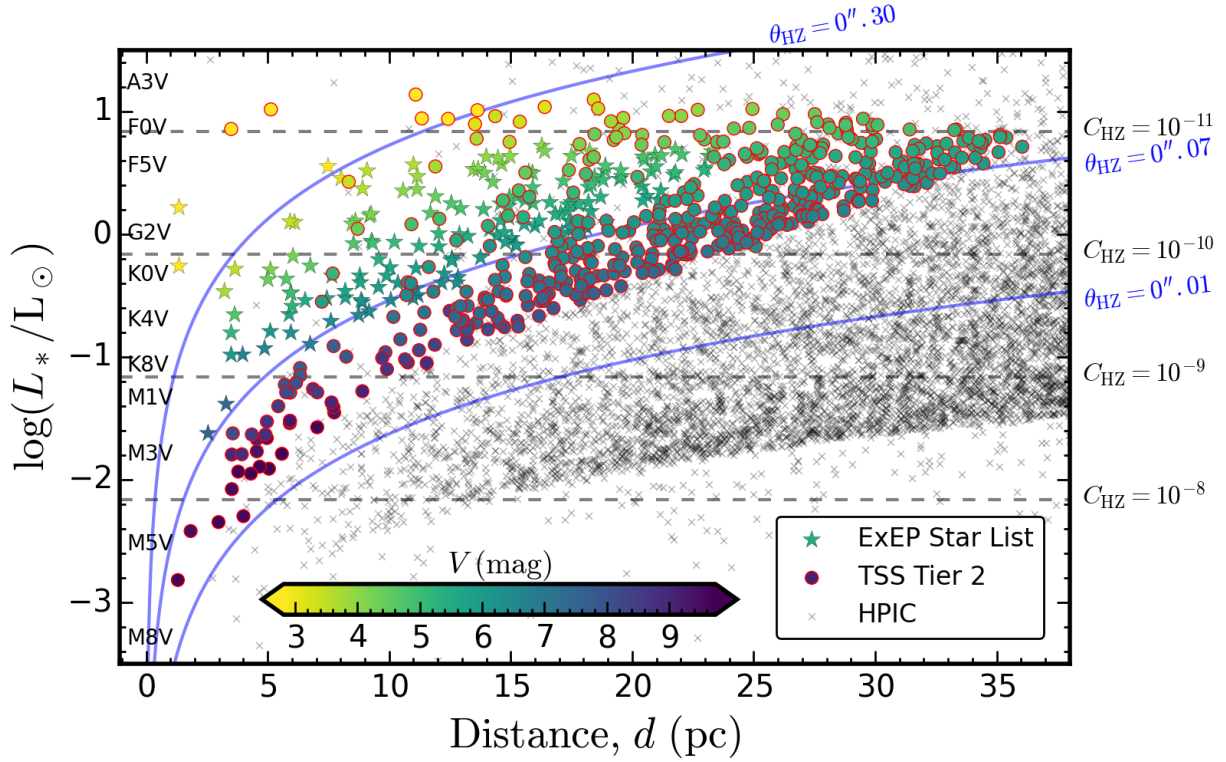


Figure 1.5: Potential target stars for HWO’s future exoEarth survey in distance vs. luminosity space. The 164 stars from the ExEP Mission Star List (Mamajek and Stapelfeldt 2024) are shown by the “ $\star$ ” symbols. The apparent V magnitudes are indicated by the colorbar. The TSS Tier 2 target list (Tuchow et al. 2025) is shown by red-outlined circles. Lines of constant planet–star contrast ratio (C_{HZ}) and middle-HZ angular separation (θ_{HZ}) are plotted assuming a $1 R_{\oplus}$ planet with geometric albedo $A_g = 0.2$ at a phase angle of $\pi/2$. The full HPIC list (Tuchow et al. 2024) is also shown for reference. Note that the vast majority of these stars are F, G, K, and early M stars.

standing goal of discovering true Earth twins and other Solar System analogs orbiting more “Sun-like” stars (i.e., F, G, and K types).

Toward Habitable Worlds Around Sun-like Stars

While rocky planets orbiting (late) M dwarfs remain an interesting topic of study, the work presented in subsequent chapters of this dissertation focus on the search for exoEarths around Sun-like stars. Future generations of EPRV and photometric searches will continue improving toward establishing robust samples of smaller, lower-mass planets in the HZs of FGK dwarfs (e.g., Rauer et al. 2014; Brewer et al. 2020; Gupta et al. 2025), but even more substantial gains in discovering and characterizing potentially habitable worlds will be realized by future missions capable of measuring photons directly emitted or reflected by small rocky planets. While current ground-based

imaging can detect the thermal glow of giant, recently formed planets, future direct imaging instruments on 30 m class extremely large telescopes (ELTs) will be able to measure MIR emission from planets $< 4 R_{\oplus}$ around stars of spectral types A–K within 6.5 pc, enabling estimates of their luminosities, equilibrium temperatures, radii, and perhaps atmospheric compositions via multi-band photometry spectroscopy (e.g., Bowens et al. 2021).

Detailed atmospheric characterization of a statistical sample of Earth-size exoplanets demands a much larger search volume, likely requiring the exquisite precision, stability, and broad spectral bandpass that only space-based missions can achieve. In the MIR, the European-led Large Interferometer For Exoplanets (LIFE) mission will utilize a space-based nulling interferometer to spatially separate the thermal emission from exoplanets and their host stars to conduct atmospheric characterization of dozens of small planet in order to understand their diversity and search for habitable worlds and potential biosignatures (e.g., Quanz et al. 2022b,a; Menti et al. 2024). At shorter wavelengths from the NIR–UV, NASA’s planned Habitable Worlds Observatory (HWO) will use a coronagraph or starshade for starlight suppression in order to collect photons scattered or transmitted through the atmospheres of rocky HZ planets orbiting Sun-like stars to search for signatures of global biospheres and habitability (e.g., National Academies of Sciences, and Medicine, Engineering 2021; Stark et al. 2024b; Feinberg et al. 2026). Scientific preparation for missions like LIFE and HWO is a key focus of this dissertation (Chapters 3–5), and many of the stars and planets discussed here are potential targets for those missions. Specifically, the work presented in Chapters 3–5 has been informed by NASA’s Exoplanet Exploration Program (ExEP) Mission Star List of provisional targets for HWO’s exoEarth survey (Mamajek and Stapelfeldt 2024). Some properties of these stars are shown in Figure 1.5, along with additional potential target stars for future exoEarth imaging missions from NASA’s Target Stars and Systems (TSS) Working Group (Tuchow et al. 2025) and the HWO Preliminary Input Catalog (HPIC; Tuchow et al. 2024). These stars are referenced extensively in this work, and may one day give us a direct window into potentially habitable exoEarths and the first ever “Family Portrait” (Figure 1.1) of a solar system beyond our own.

1.4 Dissertation Overview

This dissertation broadly seeks to bridge existing knowledge of exoplanetary systems from the last 3 decades to future discoveries of potentially habitable worlds orbiting Sun-like stars. The following chapters dig deeper into several themes represented in Figure 1.4 as factors affecting habitability, with significant emphasis on how the observations and analyses presented here today will enable science and engineering trade studies that guide future facilities toward detecting Earth-like worlds. The rest of this dissertation is organized as follows.

In Chapter 2, I present a study of the detectability and long-term stability of potentially habitable exomoons orbiting HIP 41378 f, a temperate Jovian planet with an anomalously low apparent density in a multiplanet system. I present *astroQTPy*, an open-source Python package that implements a quadtree data structure to accelerate N -body experiments for hierarchical star–planet–moon systems. Combining these a suite of N -body simulations with equilibrium tide evolution

models and photodynamical transit constraints, I demonstrate that long-term stable, Earth-sized moons around HIP 41378 f are dynamically viable and consistent with K2 and HST light curve observations. This work therefore demonstrates that HIP 41378 f may be a promising laboratory for testing theories of exomoon formation and habitability with future extremely precise photometric facilities (e.g., PLATO). While no confirmed exomoons are yet known, this work shows that such moons could persist around giant planets in the optimistic HZs of Sun-like stars.

In Chapter 3, I present an analysis of the FUV–MIR spectral energy distributions of 164 nearby FGKM stars that are promising targets for future exoEarth surveys (e.g., with HWO). I apply a Bayesian Model Averaging framework to derive robust stellar parameters (e.g., T_{eff} , $L_{\star}$) that are relevant to planetary habitability (Section 1.2), then compile those stellar parameters in a public catalog with stellar abundance measurements, TESS flare rates, optical variability, and X-ray fluxes from the literature. This combined dataset represents an important initial step toward enabling missions like HWO because it informs the selection of exoEarth survey target stars and the overall mission architecture by providing key inputs for modeling rocky planet interiors, out-gassed atmospheres, and global biosignatures.

Continuing with the theme of precursor science for future exoEarth surveys, I present an archival RV survey of over 120 nearby stars in Chapter 4 to determine the efficiency of past planet searches, detect and characterize giant companions, and constrain their system architectures. I present a catalog of $>150,000$ public RV measurements and stellar activity indicator measurements obtained from 23 spectrographs around the world spanning a total baseline of 36 yr, which were compiled with the help of over 60 volunteers through the RV Hunters community science project at UC Berkeley. Using the RV catalog, I determine empirical mass sensitivity limits to inform long-baseline RV monitoring programs that will improve planetary system context and constrain the presence of disruptive giant companions in the HZs of potential exoEarth imaging survey targets.

Motivated by the results of the archival RV survey, I present preliminary results from ongoing RV surveys of potential exoEarth imaging targets with APF in Chapter 5. Using ~ 1.5 yr of APF observations of the late F dwarf HD 5015, I present the discovery of a potential giant companion on an eccentric orbit which could be dynamically incompatible with stable Earth-size planets in the HZ. Because the APF observations capture the periastron passage but not the full orbit, the precise period of the companion cannot yet be determined without additional monitoring of the system. However, the detection of this potential giant companion demonstrates the importance of systematic follow-up of previously unobserved nearby systems whose HZs must be scrutinized in order to maximize efficiency of future exoEarth imaging surveys.

Finally, I provide concluding remarks in Chapter 6. I present a final summary of this work as well as research I contributed to beyond what is presented in this dissertation. Lastly, I discuss future directions of the field and potential next steps proceeding from this dissertation.

Chapter 2

Exomoons Orbiting an Inflated Temperate Giant

A previous version of this chapter was published in: Harada, C. K., Dressing, C. D., Alam, M. K., Kirk, J., López-Morales, M., Ohno, K., Akinsanmi, B., Barros, S. C. C., Buchhave, L. A., Collier Cameron, A., Crossfield, I. J. M., Dai, F., Gao, P., Giacalone, S., Grouffal, S., Lillo-Box, J., Mayo, A. W., Mortier, A., Santerne, A., Santos, N. C., Sousa, S. G., Turtelboom, E. V., Vanderburg, A., & Wheatley, P. J., 2023, The Astronomical Journal, 166(5), 208.



Moons orbiting exoplanets (“exomoons”) may hold clues about planet formation, migration, and habitability. In this work, we investigate the plausibility of exomoons orbiting the temperate ($T_{\text{eq}} = 294 \text{ K}$) giant ($R = 9.2 R_{\oplus}$) planet HIP 41378 f, which has been shown to have a low apparent bulk density of 0.09 g cm^{-3} and a flat near-infrared transmission spectrum, hinting that it may possess circumplanetary rings. Given this planet’s long orbital period ($P \approx 1.5 \text{ yr}$), it has been suggested that it may also host a large exomoon. Here, we analyze the orbital stability of a hypothetical exomoon with a satellite-to-planet mass ratio of 0.0123 orbiting HIP 41378 f. Combining a new software package, `astroQTy`, with `REBOUND` and `EqTide`, we conduct a series of N-body and tidal migration simulations, demonstrating that satellites up to this size are largely stable against dynamical escape and collisions. We simulate the expected transit signal from this hypothetical exomoon and show that current transit observations likely cannot constrain the presence of exomoons orbiting HIP 41378 f, though future observations may be capable of detecting exomoons in other systems. Finally, we model the combined transmission spectrum of HIP 41378 f and a hypothetical moon with a low-metallicity atmosphere and show that the total effective spectrum would be contaminated at the $\sim 10 \text{ ppm}$ level. Our work not only demonstrates the feasibility of exomoons orbiting HIP 41378 f but also shows that large exomoons may be a source of uncertainty in future high-precision measurements of exoplanet systems.

2.1 Introduction

The discovery and characterization of extrasolar moons (i.e., “exomoons”) will play an important role in developing a more complete understanding of planetary systems. As remnants of planet formation, moons may provide useful information about the formation and evolution of exoplanets (e.g., Sasaki et al. 2010; Heller et al. 2014; Spalding et al. 2016; Ronnet et al. 2018). Moon–planet interactions may also be crucial for the long-term stability of exoplanet habitability. For example, moons may stabilize planetary obliquity (Laskar et al. 1993; Lissauer et al. 2012) and drive tidal heating (e.g., Piro 2018a), thereby significantly affecting planetary climates. Moreover, sufficiently heated exomoons may themselves be capable of hosting life, providing an alternative path to habitability beyond conventional habitable-zone terrestrial planets (e.g., Heller and Barnes 2013; Heller et al. 2014).

Despite the large number of confirmed exoplanets surveyed to date (> 6000), there has yet to be a confirmed detection of an exomoon, largely due to the minuscule signals that putative moons imprint on measurements of their exoplanet hosts. Though tentative evidence for exomoons exists (Teachey and Kipping 2018; Kipping et al. 2022), robustly detecting exomoons is likely beyond the reach of current technology. Nonetheless, theoretical constraints on exomoon formation and evolution can provide valuable insight into plausible satellite-hosting exoplanets, and aid in the interpretation of future high-precision observations. For example, numerical N-body simulations have set limits on exomoon eccentricities and semimajor axes that are plausibly stable over long timescales (e.g., Domingos et al. 2006; Payne et al. 2013; Rosario-Franco et al. 2020). Moreover, previous studies have investigated how tidal interactions between bodies can result in the radial migration of an exomoon, leading to its eventual escape or tidal disruption by the planet (e.g., Barnes and O’Brien 2002; Sasaki et al. 2012; Sasaki and Barnes 2014; Piro 2018a; Sucerquia et al. 2019; Quarles et al. 2020; Jagtap et al. 2021), as well as the effects of planetary migration on exomoon stability (e.g., Alvarado-Montes et al. 2017; Sucerquia et al. 2020).

Here, we investigate the plausibility of exomoons orbiting the temperate low-mass Jovian planet HIP 41378 f. The host star HIP 41378 is a bright ($V \approx 8.9$), slightly evolved late F-type star ($T_{\text{eff}} = 6320$ K, $\log g = 4.294$, $[\text{Fe}/\text{H}] = -0.10$, $M_{\star} = 1.16 M_{\odot}$; Santerne et al. 2019) with five known transiting exoplanets (Vanderburg et al. 2016a; Berardo et al. 2019). The system was initially observed over the course of about 75 days during Campaign 5 (C5) of the extended Kepler mission (K2; Borucki et al. 2010; Howell et al. 2014), after which the two innermost planets were classified as sub-Neptunes ($R_{p,b} \approx 2.9 R_{\oplus}$, $R_{p,c} \approx 2.6 R_{\oplus}$) orbiting in a near 2:1 resonance at approximately 15.6 and 31.7 days (Vanderburg et al. 2016a). However, only single transits were initially observed for the three outer planets ($R_{p,d} \approx 4.0 R_{\oplus}$, $R_{p,e} \approx 5.5 R_{\oplus}$, $R_{p,f} \approx 10 R_{\oplus}$), and hence their orbital periods and ephemerides could not be well constrained.

More precise limits on the orbits of planets d and f were later derived after one additional transit was observed for each planet during C18 of the K2 mission (Becker et al. 2019; Berardo et al. 2019). A subsequent third transit observation of planet f with the ground-based Next Generation Transit Survey (NGTS; Wheatley et al. 2018) confirmed its orbital period and suggested the presence of transit timing variations (TTVs; Bryant et al. 2021). Furthermore, radial velocity monitoring of the host star over hundreds of epochs was used to constrain the masses of all of the

Median and 68.3% credible interval			
Planet Parameters	HIP 41378 b	HIP 41378 c	HIP 41378 d
Orbital period, P (days)	$15.57208 \pm 2 \times 10^{-5}$	$31.70603 \pm 6 \times 10^{-5}$	$278.3618 \pm 5 \times 10^{-4}$
Eccentricity, e	0.07 ± 0.06	$0.04^{+0.04}_{-0.03}$	0.06 ± 0.06
Semi-major axis, a (AU)	$0.1283 \pm 1.5 \times 10^{-3}$	$0.2061 \pm 2.4 \times 10^{-3}$	0.88 ± 0.01
Inclination, i ($^\circ$)	88.75 ± 0.13	$88.477^{+0.035}_{-0.061}$	89.80 ± 0.02
Radius, R_p ($R_\oplus$)	2.595 ± 0.036	2.727 ± 0.060	3.54 ± 0.06
Mass, M_p ($M_\oplus$)	6.89 ± 0.88	4.4 ± 1.1	$< 4.6^*$
Bulk density, ρ_p (g cm^{-3})	2.17 ± 0.28	1.19 ± 0.30	$< 0.56^*$
Equilibrium temperature, T_{eq} (K) [†]	959^{+9}_{-5}	757^{+7}_{-4}	367^{+3}_{-2}
Insolation flux, S ($S_\oplus$)	140^{+5}_{-3}	54^{+2}_{-1}	$3.01^{+0.11}_{-0.06}$
Planet Parameters	HIP 41378 e	HIP 41378 f	
Orbital period, P (days)	369 ± 10	$542.07975 \pm 1.4 \times 10^{-4}$	
Eccentricity, e	0.14 ± 0.09	$0.004^{+0.009}_{-0.003}$	
Semi-major axis, a (AU)	$1.06^{+0.03}_{-0.02}$	1.37 ± 0.02	
Inclination, i ($^\circ$)	$89.84^{+0.07}_{-0.03}$	$89.971^{+0.01}_{-0.008}$	
Radius, R_p ($R_\oplus$)	4.92 ± 0.09	9.2 ± 0.1	
Mass, M_p ($M_\oplus$)	12 ± 5	12 ± 3	
Bulk density, ρ_p (g cm^{-3})	0.55 ± 0.23	0.09 ± 0.02	
Equilibrium temperature, T_{eq} (K) [†]	335 ± 4	294^{+3}_{-1}	
Insolation flux, S ($S_\oplus$)	2.1 ± 0.1	$1.24^{+0.05}_{-0.02}$	
Stellar Parameters	HIP 41378		
Effective temperature, T_{eff} (K)	6320^{+60}_{-30}		
Surface gravity, $\log g$ (cgs)	4.294 ± 0.006		
Metallicity, [Fe/H] (dex)	-0.10 ± 0.07		
Mass, $M_\star$ ($M_\odot$)	1.16 ± 0.04		
Radius, $R_\star$ ($R_\odot$)	1.273 ± 0.015		
Age, $\tau_\star$ (Gyr)	3.1 ± 0.6		
Distance from Earth, D (pc)	103 ± 2		

[†] Assumes zero albedo and full heat redistribution.

* 95% credible upper limit.

Table 2.1: Summary of HIP 41378 System Parameters.

planets in the system, providing new insights into their physical properties. Santerne et al. (2019) conducted a joint analysis using the two campaigns of K2 photometry together with 464 epochs of radial velocity measurements from the High Accuracy Radial velocity Planet Searcher (HARPS) spectrograph at the 3.6-m ESO telescope in Chile, the HARPS-North spectrograph at the 3.58-m TNG telescope on the Canary Islands, Spain, the High Resolution Echelle Spectrometer (HIRES) at the 10-m Keck telescope on Mauna Kea, Hawaii, and the Prime Focus Spectrograph at the 8.2-m Subaru telescope on Mauna Kea, Hawaii. They reported updated planet radii, masses, bulk densities, and orbital parameters for the five transiting planets, as well as a tentative detection of a sixth nontransiting planet candidate. A summary of the planet parameters from Santerne et al. (2019) is shown in Table 2.1.

The largest and outermost planet in the system, HIP 41378 f, orbits near the inner edge of the

system’s habitable zone with a period of about 1.5 years. Intriguingly, the planet has an inferred radius of $9.2 R_{\oplus}$ but it has a mass of only $12 M_{\oplus}$, making it one of the lowest bulk density planets currently known ($\rho = 0.09 \text{ g cm}^{-3}$; Santerne et al. 2019). It has been proposed that such low bulk densities in exoplanets could be explained by atmospheric outflows entraining optically thick photochemical hazes, which act to increase the planet’s apparent radius in transit (Wang and Dai 2019; Gao and Zhang 2020; Ohno and Tanaka 2021). However, this mechanism may not be compatible with HIP 41378 f because of the planet’s relatively high mass and cool equilibrium temperature (e.g., see Equation (34) of Ohno and Tanaka 2021). Moreover, Belkovski et al. (2022) showed that HIP 41378 f would require a very high envelope mass fraction ($\gtrsim 75\%$) to remain in hydrostatic balance, in tension with the core accretion paradigm of planet formation.

An alternative explanation for the apparently low density of HIP 41378 f is that the planet itself is significantly smaller, but is accompanied by a system of optically thick circumplanetary rings (Zuluaga et al. 2015; Akisanmi et al. 2020; Piro and Vissapragada 2020). Such a ring system, if viewed at a sufficiently high inclination, would effectively increase the observed transit depth while allowing the planet to have a bulk density more typical of sub-Neptunes. For example, Akisanmi et al. (2020) demonstrated that observations of HIP 41378 f are consistent with a $3.7 R_{\oplus}$ ($\rho = 1.2 \text{ g cm}^{-3}$) planet with opaque rings extending from 1.05 to 2.6 planet radii. In addition, the presence of optically thick rings potentially causes a featureless transmission spectrum (Ohno and Fortney 2022; Ohno et al. 2022). Interestingly, our recent observations of HIP 41378 f taken with the Widefield Camera 3 (WFC3) aboard the Hubble Space Telescope (HST) reveal a featureless near-infrared (1.1–1.7 μm) transmission spectrum (HST-GO Program 16267; Alam et al. 2022). Within the precision of these observations, we currently cannot distinguish between circumplanetary rings ($\chi_r^2 \approx 1.03$), high-altitude photochemical hazes ($\chi_r^2 \approx 0.97$), or a high-metallicity atmosphere ($\chi_r^2 \approx 1.84$). Future spectral observations at mid-infrared wavelengths (e.g., with JWST/MIRI) may be able to distinguish between these scenarios (Alam et al. 2022).

The possibility of a circumplanetary ring system around HIP 41378 f naturally raises the question of whether the planet could also host moons. For example, Saillenfest et al. (2023) concluded that the migration of a former moon is a viable formation pathway for the proposed ring and tilt of HIP 41378 f. More generally, moons and circumplanetary rings are ubiquitous in the outer solar system, and earlier studies have suggested that rings are originally formed from moons (e.g., Canup 2010), or vice versa (Crida and Charnoz 2012).

Because the Hill radius scales linearly with the distance of a planet from its host star, the large separation of HIP 41378 f from its host star relative to the population of hot Jupiters ($P \lesssim 10$ days) makes it a favorable environment for exomoons. While HIP 41378 f itself is likely not habitable due to its high gas fraction, its temperate orbital separation raises the possibility that it hosts habitable exomoons. We note that the habitability of icy moons in the outer solar system is still an open question. Though the detailed level of characterization required to assess exomoon habitability, or even confirm exomoon detections at all, is beyond current instrumental sensitivity, it may be important to consider the extent to which the presence of exomoons could manifest as a source of uncertainty in measurements of cool gaseous exoplanets, especially as we look toward future high-precision facilities such as ground-based extremely large telescopes (ELTs) and large space-based UV/optical/IR observatories (e.g., Dalba et al. 2015; The LUVOIR Team 2019).

Here we assess the stability of exomoons orbiting HIP 41378 f using a suite of numerical N -body simulations and models of tidal evolution. Then, from the results of our stability analysis, we simulate the observable impact of a large exomoon on the white light curve and infrared transmission spectrum of HIP 41378 f. The rest of this chapter is organized as follows: in Section 2.2 we describe our theoretical methods used to constrain the allowable range of parameters for a stable moon orbiting HIP 41378 f. In Section 2.3, we present the results from our analysis and discuss the future observational implications. We conclude with a summary in Section 2.4.

2.2 Methods

We first consider whether it is feasible that HIP 41378 f could host an exomoon over the system’s lifetime. Here we outline a theoretical approach to investigating this possibility. First, we apply a suite of dynamic simulations to assess the long-term orbital stability of satellites around HIP 41378 f. We then separately consider the effects of tidal friction on the orbits of satellites and whether tidal migration can further destabilize the system. Throughout this section, we assume that HIP 41378 f has properties consistent with measurements from Santerne et al. (2019), and we do not self-consistently include circumplanetary rings in our simulations.

N -body Simulations

Three-body Simulation

Because HIP 41378 is a multiplanet system, gravitational interactions between neighboring planets may affect the long-term stability of a satellite orbiting planet f. Before considering the effects of additional planets, we start with an idealized three-body system with only one satellite orbiting planet f, which is in orbit around HIP 41378. To simulate the dynamical evolution of the system, we use the REBOUND N -body code (Rein and Liu 2012) and the 15th-order “IAS15” integrator with adaptive time stepping (Rein and Spiegel 2015).

In these simulations, we fix the stellar mass and the mass and semimajor axis of planet f to the values from Santerne et al. (2019) provided in Table 2.1. Given a vast range of possible satellite configurations and properties, which would be computationally prohibitive to fully explore, we chose to consider a satellite with the largest satellite-to-planet mass ratio observed in the solar system (i.e., the Moon–Earth system). This choice allows us to explore a physically motivated scenario that maximizes the potential signal produced by the satellite: larger satellites may be exceedingly rare, based on the population of hundreds of moons in the solar system, and smaller moons are far less likely to be detected. Therefore, as an extreme case, we consider a satellite of HIP 41378 f with a mass of $M_s = 0.15 M_\oplus$ to be consistent with the satellite-to-planet mass ratio for the Earth–Moon system ($M_M/M_\oplus \approx 0.0123$). We prescribe the satellite an Earth-like rocky composition ($\rho_s = 5.5 \text{ g cm}^{-3}$), yielding a radius of $R_s = 0.53 R_\oplus$ (or approximately the radius of Mars).

For simplicity, the moon is initiated on a circular orbit around planet f, then, in a similar fashion to previous studies that estimated stability limits of hierarchical star-planet-moon systems

(e.g., Rosario-Franco et al. 2020; Jagtap et al. 2021; Quarles et al. 2021), each simulation is run for a duration of up to 10^5 yr. A simulation is halted and marked as “unstable” if either of the following criteria are met:

1. the satellite collides with the planet,¹ or
2. the satellite escapes the gravitational influence of the planet by crossing outside of the planet’s Hill radius, defined as

$$R_H = a_p \left(\frac{M_p}{3M_\star} \right)^{1/3}, \quad (2.1)$$

where a_p is the planet’s semimajor axis, and M_p and $M_\star$ are the masses of the planet and star, respectively.

As an initial test case, we first reproduced the results of Domingos et al. (2006) and Rosario-Franco et al. (2020) by assessing the stability of the hypothetical satellite as a function of the initial planet-moon semimajor axis, a_s , and the eccentricity of planet f’s orbit, e_f . Because the eccentricity of planet f is well constrained by observations (see Table 2.1), the main purpose of this setup was to benchmark our N-body code and confirm that it generates expected results. We provide a more thorough description of this procedure in Appendix 2.A. In summary, we qualitatively recover a similar trend in the stability of the exomoon as a function of (a_s, e_f) as previous studies, and the critical stability limit we recover for circular planetary orbits, $a_{\text{crit}} \approx 0.41 R_H$, is consistent with published values (Rosario-Franco et al. 2020).

Next, we investigate how the satellite’s orbital stability depends on its initial inclination. Our setup is similar to that of our benchmark simulations and the work of Domingos et al. (2006) and Rosario-Franco et al. (2020), but here we fix the eccentricity of planet f to its measured 95% confidence upper limit of $e_f = 0.035$ (Santerne et al. 2019), while varying the satellite’s orbital inclination, i_s , and semimajor axis, a_s .² We constrained our simulations to vary i_s from $\cos i_s = 0$ (aligned with the planet’s reference plane) to $\cos i_s = 1$ (perpendicular to the planet’s reference plane), and a_s from $0.1R_H$ to $0.8R_H$. Here, R_H is the Hill radius defined in Equation (2.1): $R_H \approx 0.03 \text{ au} \approx 76R_p$. The planet and satellite are both initialized with their ascending node longitudes and pericenter arguments set to zero ($\Omega = \omega = 0^\circ$). The planet’s mean anomaly is also set to zero ($\mathcal{M}_f = 0^\circ$).

Then, to efficiently explore the moon’s stability within the defined parameter space, we run a suite of N -body simulations using a quadtree data structure implemented in the `astroQTPy` package³ (Harada 2023). `astroQTPy` is based on the transit injection and recovery quadtree algorithm

¹We also considered imposing an inner stability bound defined by the planet’s Roche limit radius, defined as $R_{\text{Roche}} \simeq 2.4R_s(M_p/M_s)^{1/3}$. However, due to the planet’s low observed mass, the conventional definition of the Roche limit yields a nonphysical distance smaller than the planet’s measured radius. Without further information about the planet’s interior structure or whether it possesses a circumplanetary ring system, we chose to set the inner separation bound equal to the planet’s observed radius instead.

²We also tested a zero-eccentricity case but determined that this has a negligible impact on the results. In general, lower-eccentricity systems are expected to be more stable regardless of the satellite’s inclination (see Appendix 2.A).

³<https://github.com/CalebHarada/astroQTPy>

Parameter	Distribution (3-body)	Distribution (4-body)
Planet f		
Mass, M_f ($M_\oplus$)	12.3	$\mathcal{T}(12.3, 3.1, 0.0, \infty)$
Orbital period, P_f (days)	542.0798	$\mathcal{N}(542.0798, 0.0001)$
Eccentricity, e_f	0.035	$\mathcal{T}(0.005, 0.005, 0.0, 1.0)$
Mean anomaly, $\mathcal{M}_f$	$\mathcal{U}(0.0, 2\pi)$	$\mathcal{U}(0.0, 2\pi)$
Argument of periastron, ω_f ($^\circ$)	0.0	$\mathcal{T}(231.0, 120.0, 0.0, 360.0)$
Inclination, i_f ($^\circ$)	90.0	$\mathcal{T}(89.97, 0.01, 0.0, 90.0)$
Planet e		
Mass, M_e ($M_\oplus$)	N/A	$\mathcal{T}(12.0, 5.0, 0.0, \infty)$
Orbital period, P_e (days)	N/A	[344.0, 394.0)
Eccentricity, e_e	N/A	[0.0, 0.3)
Mean anomaly, $\mathcal{M}_e$	N/A	$\mathcal{U}(0.0, 2\pi)$
Argument of periastron, ω_e ($^\circ$)	N/A	$\mathcal{T}(114.0, 55.0, 0.0, 360.0)$
Inclination, i_e ($^\circ$)	N/A	$\mathcal{T}(89.84, 0.05, 0.0, 90.0)$
Satellite		
Mass, M_s ($M_\oplus$)	0.15	0.15
Semi-major axis, a_s (R_H)	[0.1, 0.8)	$\mathcal{U}(0.1, 0.4)$
Eccentricity, e_s	0.0	0.0
Mean anomaly, $\mathcal{M}_s$	$\mathcal{U}(0.0, 2\pi)$	$\mathcal{U}(0.0, 2\pi)$
Argument of periastron, ω_s ($^\circ$)	0.0	0.0
Cosine of inclination, $\cos(i_s)^\dagger$	[0.0, 1.0)	$\mathcal{U}(0.0, 1.0)$

Note. $\mathcal{N}(\mu, \sigma)$ is a normal distribution with mean μ and standard deviation σ ; $\mathcal{U}(a, b)$ is a uniform distribution bounded between a and b ; $\mathcal{T}(\mu, \sigma, a, b)$ is a truncated normal distribution with mean μ and standard deviation σ and bounded between a and b .

† The inclination of the satellite's orbit, i_s , is defined from the reference plane of the planet's orbit.

Table 2.2: Parameter Distributions for N -body Simulations.

originally described by Ment and Charbonneau (2023). We initially create a 4×4 stability grid by evenly subdividing the parameter space in $\cos i_s$ and a_s . Within each grid cell, we run 25 independent N -body simulations with the initial conditions $\cos i_s$ and a_s drawn from uniform distributions.⁴ The satellite's initial mean anomaly, $\mathcal{M}_s$, is also chosen randomly from a uniform distribution for each simulation (see Table 2.2). Each simulation is run forward for up to 10^5 yr, and then the fractional stability of each cell, f_{stab} , is calculated as the fraction of simulations (out of 25) that satisfy the stability criteria defined above.

In this setup, each grid cell corresponds to a child node of the quadtree which occupies $(1/4) \times (1/4)$ of the total initial parameter space $\{\cos i_s\} \times \{a_s\}$. The grid is then iteratively refined to higher resolution by splitting each node into four equal child nodes where the following criteria are satisfied:

1. the fractional stability of the node differs from that of a neighboring node by at least 20%,⁵ and

⁴We experimented with a larger number of simulations per grid cell, but this had no major impact on our results.

⁵We repeated this procedure assuming a more stringent splitting threshold of 10%, but we found that this had no significant impact on the results.

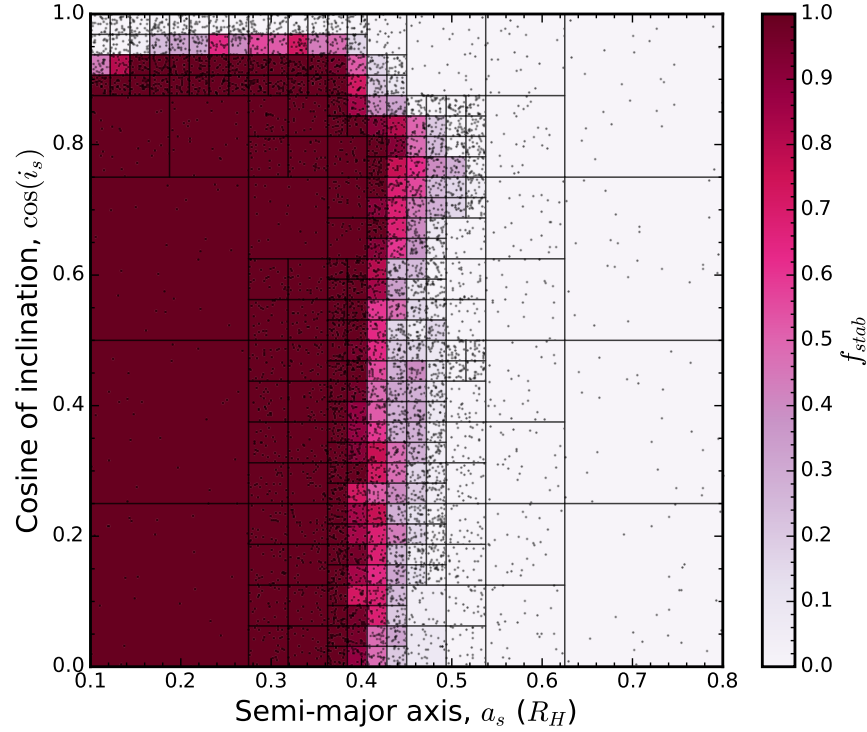


Figure 2.1: Three-body orbital stability map for a system consisting of the star HIP 41378, planet f, and planet f’s hypothetical satellite as a function of the satellite’s semimajor axis a_s (expressed in terms of the Hill radius, R_H) and the cosine of the satellite’s inclination $\cos i_s$ (with respect to the planet’s reference plane). The color of each grid cell corresponds to the fraction f_{stab} of the 25 simulations contained inside the cell (shown as points) which survive for 10^5 yr. Completely unstable regions are represented by the lightest areas, while completely stable regions are shown by the darkest red regions. Note that moons with exceptionally high orbital inclinations ($\cos i_s \gtrsim 0.8$) tend to become unstable due to Kozai–Lidov oscillations, and there are no stable orbits for $\cos i_s \gtrsim 0.95$.

2. each of the resulting child nodes occupies no less than $(1/32) \times (1/32)$ of the total parameter space.

After a node has split, all of the completed simulations stored within that node are distributed to its four child nodes according to their $\cos i_s$ and a_s values, and each child node is subsequently filled by running more N -body simulations until each node contains a maximum of 25 simulations. This process is repeated until the splitting criteria are no longer met for any nodes. Therefore, the total number of N -body simulations run for the completed stability map lies between $4 \times 4 \times 25 = 400$ and $32 \times 32 \times 25 = 25,600$. Figure 2.1 shows the final stability map resulting from this setup, which we will discuss further in Section 2.3.

Four-body Simulation

We next run an additional set of N -body simulations, now including the second-outermost planet in the system, HIP 41378 e (which is separated from planet f by ~ 10 mutual Hill radii). It is beyond the scope of this work to simulate the global stability of the system, so we do not include planet b ($P = 15.57$ days), planet c ($P = 31.71$ days), or planet d ($P = 278.36$ days) in our simulations in order to reduce the complexity of the problem and lower computational costs. For the purpose of studying the stability of a satellite around planet f, this is a valid assumption given that the force of gravity on planet f due to the three inner planets at closest approach is several orders of magnitude smaller than that of planet e (planets b, c, and d are separated from planet f by approximately 65, 61, and 19 mutual Hill radii, respectively). Moreover, the TTVs of planet f are thought to be dominated by a 2:3 period commensurability with planet e (Bryant et al. 2021).

For this case, our setup is similar to that of our three-body simulations, but we now evaluate the fractional stability as a function of planet e’s orbital period, P_e , and eccentricity, e_e . Furthermore, to account for observational uncertainties in the masses and orbits of planets e and f, we randomly draw other system parameters that are consistent with the results of Santerne et al. (2019). For each trial simulation we randomly draw the mass, argument of pericenter, and inclination of planets e and f, and the period and eccentricity of planet f from normal distributions with standard deviations consistent with the uncertainties given in Table 2.1.

For the satellite of planet f, we assume a circular orbit and randomly draw the cosine of the inclination (with respect to the planet’s orbital plane) from a uniform distribution between 0 and 1, and the initial semimajor axis between 0.1 and $0.4R_H$ (i.e., within the stability limits for a low-eccentricity host planet derived from our benchmark simulations). We assume the same fixed stellar mass and satellite mass as before, and initialize each object with a random mean anomaly between 0° and 360° . A summary of the distributions used to select parameters for each iteration is provided in Table 2.2. Figure 2.2 shows an example of 20 random realizations of this system setup for fixed values of P_e and e_e .

With the addition of planet e to our simulations, we update the stability criteria defined for the three-body simulations, such that a system is also flagged as “unstable” if planet e enters the Hill sphere of planet f, or if any planet’s orbit crosses the orbit of another planet. The latter criterion places an upper limit on the eccentricity of planet e for a given orbital period due to the intersection of its periastron distance with the expected orbit of planet d (note, however, that we do not explicitly include planet d in the N -body simulations). Assuming that planet d has a circular orbit,⁶ this limit is set by

$$P_{e,\text{crit}}(e_e) \simeq \frac{2\pi}{\sqrt{GM_\star}} \left(\frac{a_d}{1 - e_e} \right)^{3/2}, \quad (2.2)$$

where a_d is the semi-major axis of planet d and G is the Newtonian gravitational constant. Note that for the measured eccentricity of planet e ($e_e = 0.14$; Santerne et al. 2019), $P_{e,\text{crit}} \approx 351$ days, which is only within $\sim 1.8\sigma$ of the measured period of planet e ($P_e = 369 \pm 10$ days; Santerne et al. 2019).

⁶The eccentricity reported by Santerne et al. (2019) is fully consistent with a circular orbit (Table 2.1).

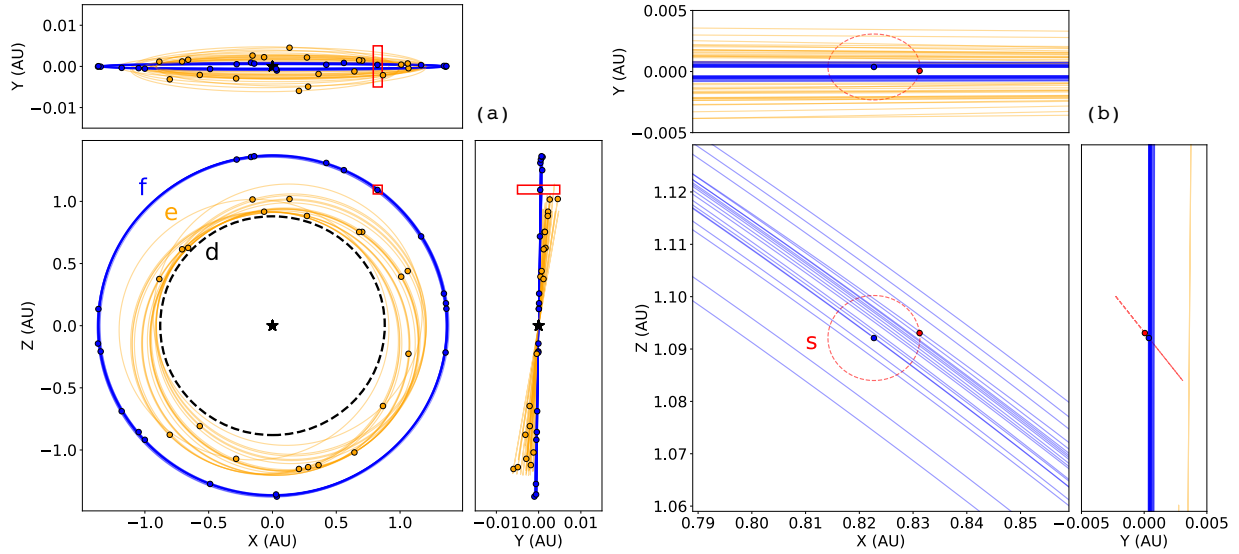


Figure 2.2: Example two-dimensional projections of the initial positions and orbits of each object in the four-body simulations, including planet e. Panel (a) shows the top-down and edge-on projections of 20 random realizations of the system, with the initial orbits (lines) and positions (points) of planet e shown in orange, and the initial orbits and positions of planet f shown in blue. The black “★” symbol shows the position of the host star, and the dashed black line shows the (assumed) fixed orbital semimajor axis for planet d. The small red boxes indicate the limits of the area plotted in panel (b), which shows a zoomed-in version of the system highlighting the initial position and orbit of the satellite, marked “s” (red), orbiting planet f.

We explore the fractional stability of the system in the parameter space around this limit over a timescale of 10^5 yr, selecting a range of P_e and e_e consistent with their observed values within $\sim 2\sigma$ (see Table 2.2). Again, we start by evenly dividing the entire (P_e, e_e) parameter space into a 4×4 astroQTypy grid, and computing f_{stab} in each cell by running a set of 25 independent trials with the set of parameters described above. We then proceed by iteratively subdividing the quadtree according to the same criteria used for the three-body simulations, computing more N -body trials until no more cells can be split. The resulting stability map is shown in Figure 2.3.

Tidal Migration

In addition to gravitational interactions with other planets, tidal interactions can lead to the secular evolution of a moon’s orbit. Here we consider the possible effects of tides on the orbital stability of moons around HIP 41378 f. Here, we implement an equilibrium tide (ET) model, which assumes a simple parameterization to capture the relevant tidal processes without considering the detailed physics of the interiors of the bodies or 3D effects (see Barnes 2017, and references therein). In summary, the ET model assumes that the gravitational force of a satellite creates an elongated bulge in the planet in a state of equilibrium, whose long axis is misaligned with the line connecting the

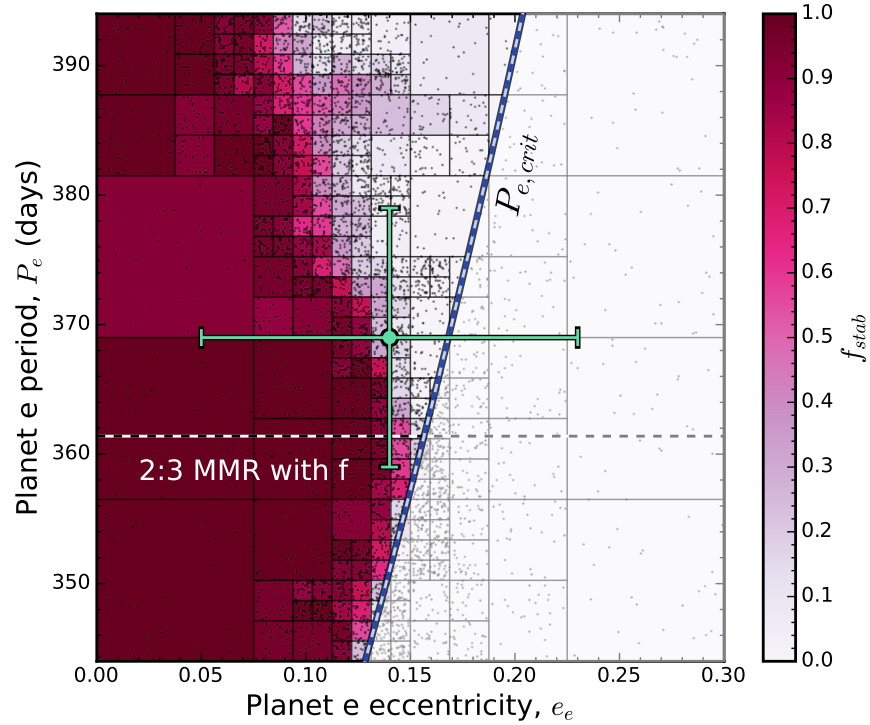


Figure 2.3: Four-body orbital stability map for a system including the star HIP 41378, planets e and f, and a satellite orbiting planet f, as a function of planet e’s initial orbital period (P_e) and eccentricity (e_e). As in Figure 2.1, the color of each grid cell shows the fraction of 25 simulations which are stable over 10^5 yr. Here, the dashed blue line shows $P_{e,crit}(e_e)$, the theoretical upper limit on planet e’s eccentricity vs. period due to the orbit of planet d (see Equation (2.2))—the region to the right of this line is unstable by definition because planet e would cross the orbit of planet d. The measured period and eccentricity of planet e from Santerne et al. (2019) are shown by the green point with error bars representing 1σ uncertainties. For reference, the period of planet e corresponding to a 2:3 mean motion resonance (MMR) with planet f is shown by the horizontal dashed line.

planet and moon centers of mass due to dissipative processes within the planet. This misalignment, or “lag” between the passage of the tidal bulge and the satellite, creates torques that lead to the secular evolution of the spin and orbital angular momenta of the two bodies.

As detailed in Barnes (2017), two distinct parameterizations of the tidal lag are well established in the literature: the “constant time lag” (CTL) model, in which the time interval between the passage of the moon and the tidal bulge is fixed, and the “constant phase lag” (CPL) model in which the phase between the moon and the tidal bulge is constant, independent of frequency. In both frameworks, the energy dissipation and tidal bulge are coupled via two parameters: the tidal Love number of degree 2, k_2 , which accounts for the internal forces of the deformed body (where $k_2 = 0$ describes a perfectly rigid body and $k_2 = 3/2$ a perfectly fluid body), and a parameter representing the offset between the tidal bulge axis and the line connecting the centers of mass.

In the CTL model, the latter parameter is referred to as the “tidal time lag,” τ , which is inversely related to the tidal quality factor Q in the CPT model. These parameters effectively describe the efficiency of the tidal response between the two bodies—larger values of τ (smaller Q) imply faster tidal evolution. While both CTL and CPL generally produce qualitatively similar results for the solar system, one may be more suitable than the other depending on the specific scenario. In this work, we choose to implement the CTL model, as it allows us to explore the impact of planetary rotation rate on the tidal evolution of the moon.

In both ET model frameworks, the tidal evolution of two bodies is described by a set of six differential equations and six free parameters: the semi-major axis a , the eccentricity e , the rotation rates of the primary and secondary bodies Ω_i , and their two obliquities ψ_i (where $i = 1, 2$ correspond to the primary and secondary bodies, respectively). Following Barnes (2017) and references therein (Mignard 1979; Hut 1981; Greenberg 2009; Leconte et al. 2010; Heller et al. 2011), the evolution for the CTL model is described by the following set of differential equations:

$$\frac{de}{dt} = \frac{11ae}{2GM_1M_2} \sum_{i=1}^2 Z_i^{\text{ctl}} \left(\cos(\psi_i) \frac{f_4(e)}{\beta^{10}(e)} \frac{\Omega_i}{n} - \frac{18}{11} \frac{f_3(e)}{\beta^{13}(e)} \right), \quad (2.3)$$

$$\frac{da}{dt} = \frac{2a^2}{GM_1M_2} \sum_{i=1}^2 Z_i^{\text{ctl}} \left(\cos(\psi_i) \frac{f_2(e)}{\beta^{12}(e)} \frac{\Omega_i}{n} - \frac{f_1(e)}{\beta^{15}(e)} \right), \quad (2.4)$$

$$\frac{d\Omega_i}{dt} = \frac{Z_i^{\text{ctl}}}{2M_i r_{g,i}^2 R_i^2 n} \left(2 \cos(\psi_i) \frac{f_2(e)}{\beta^{12}(e)} - [1 + \cos^2(\psi_i)] \frac{f_5(e)}{\beta^9(e)} \frac{\Omega_i}{n} \right), \quad (2.5)$$

and

$$\frac{d\psi_i}{dt} = \frac{Z_i^{\text{ctl}} \sin(\psi_i)}{2M_i r_{g,i}^2 R_i^2 n \Omega_i} \left(\left[\cos(\psi_i) - \frac{\xi_i}{\beta} \right] \frac{f_5(e)}{\beta^9(e)} \frac{\Omega_i}{n} - 2 \frac{f_2(e)}{\beta^{12}(e)} \right), \quad (2.6)$$

where t is time, M_i are the masses of the two bodies, R_i are their radii, and n is the mean motion. The quantity r_g is the radius of gyration, which is related to the moment of inertia by $I = M(r_g R)^2$. The above equations are averaged over the orbital period and therefore represent the mean variation of the orbital parameters.

The terms Z_i^{ctl} and ξ_i are given by

$$Z_i^{\text{ctl}} \equiv 3G^2 k_{2,i} M_j^2 (M_i + M_j) \frac{R_i^5}{a^9} \tau_i, \quad (2.7)$$

$$\xi_i \equiv \frac{r_{g,i}^2 R_i^2 \Omega_i a n}{GM_j}, \quad (2.8)$$

where $k_{2,i}$ are the second-order tidal Love numbers, τ_i are the tidal time lags, and the subscripts i and j refer to the two bodies.

The remaining terms are given by:

$$\begin{aligned}
 \beta(e) &= \sqrt{1 - e^2}, \\
 f_1(e) &= 1 + \frac{31}{2}e^2 + \frac{255}{8}e^4 + \frac{185}{16}e^6 + \frac{25}{64}e^8, \\
 f_2(e) &= 1 + \frac{15}{2}e^2 + \frac{45}{8}e^4 + \frac{5}{16}e^6, \\
 f_3(e) &= 1 + \frac{15}{4}e^2 + \frac{15}{8}e^4 + \frac{5}{64}e^6, \\
 f_4(e) &= 1 + \frac{3}{2}e^2 + \frac{1}{8}e^4, \\
 f_5(e) &= 1 + 3e^2 + \frac{3}{8}e^4.
 \end{aligned}$$

Unlike hot Jupiters ($P \lesssim 10$ days), which are expected to be in tidally synchronous rotation states with their host stars, we expect the orbital separation of HIP 41378 f to be large enough such that tidal effects from its host star are negligible. We test this assumption using a CTL equilibrium tide model as implemented in the open-source software package EqTide (Barnes 2017).

We assign the host star a mass, radius, and rotation period consistent with Santerne et al. (2019), and a solar radius of gyration, $r_{g,*} \approx 0.26$ (e.g., Claret and Gimenez 1989). We assume a Love number of $k_{2,*} = 0.5$ and a constant time lag of $\tau_* = 0.01$ s, following Barnes (2017). For the planet HIP 41378 f, we use the mass and radius reported in Santerne et al. (2019) and assume a rotation period of 10 hr, similar to that of the solar system gas giants.⁷ For the planet's radius of gyration and Love number, which are generally not measurable for exoplanets except in special cases (e.g., Akisanmi et al. 2019; Hellard et al. 2019; Barros et al. 2022), we adopt recent measurements of Jupiter from the Juno spacecraft, $r_{g,f} = 0.52$ (Ni 2018) and $k_{2,f} = 0.565$ (Idini and Stevenson 2021). Note that Saturn has similar properties, but a slightly smaller Love number of $k_2 = 0.390$ (Lainey et al. 2017), which would not significantly affect our results. For the constant time lag, we also assume a value analogous to solar system gas giants, $\tau_f = 0.00766$ s (Tokadjian and Piro 2020). For reference, $\tau \approx 0.766$ s for Neptune-like planets and $\tau \approx 638$ s for rocky planets.

Under these assumptions, we evolve the CTL model forward for a duration of 3.1×10^9 yr (approximately the age of the system), starting the planet with its currently measured semimajor axis and orbital eccentricity. We find that the relative change in the semimajor axis for planet f is $\ll 1$ ppm, and the change in rotation period is less than 0.1%. Therefore, tidal interactions between planet f and the host star are negligible, suggesting that we can safely ignore any tidal influence of the star for the purpose of studying exomoons.

Next, ignoring the influence of tides from the host star and any other planets, we investigate the tidal stability of a hypothetical moon orbiting planet f. As in the N -body experiments, we consider the extreme case of an Earth-composition satellite with the same mass ratio to planet f as the Moon–Earth system ($M_s = 0.15 M_\oplus$, $R_s = 0.53 R_\oplus$). Again, this choice is motivated by the

⁷Note that faster rotation will generally lead to tidal migration on shorter timescales.

largest moon mass ratio in the solar system and the fact that smaller moons would be much harder to measure. For the tidal properties, we arbitrarily assume that the satellite has a gyration radius similar to the value measured for Ganymede, the largest moon in the solar system: $r_{g,s} = 0.56$ (Showman and Malhotra 1999), and a tidal Love number and constant time lag consistent with measurements of rocky planets in the solar system, $k_{2,s} = 0.3$ and $\tau_s = 638$ s (e.g., Tokadjian and Piro 2020, and references therein). The mass and radius of the planet are again assumed to be the values reported in Santerne et al. (2019), and the gyration radius and Love number are set to the respective Jovian values (Ni 2018; Idini and Stevenson 2021).

Because the obliquity, constant time lag, and rotation period of the HIP 41378 f are effectively unconstrained, especially in such a low-density regime inferred from bulk mass and radius measurements, we explore how changing these parameters affects the final semimajor axis of the moon after a duration of 3.1 Gyr. Again using the EqTide code (Barnes 2017), we evolve the system forward in time starting the satellite on a tidally synchronous, circular orbit. We calculate a set of models, varying the initial semimajor axis of the moon from 4 planet radii ($\approx 0.0525R_H$) to $0.4R_H$ (i.e., the approximate stability limit for a circular orbit of planet f from the N -body results).

As an initial case, we choose τ_f to be consistent with the estimates for the solar system gas giants, $\tau_J = 0.00766$ s (Tokadjian and Piro 2020) and a rotation period similar to that of Jupiter, $P_{\text{rot},f} = 10$ hr. Then, we investigate the effect of planetary rotation rate by running the same grid of models assuming a slow planet rotation ($P_{\text{rot},f} = 24$ hr) and a fast planet rotation ($P_{\text{rot},f} = 3$ hr). For each case, we also test two extreme cases of the constant time lag by setting τ_f to 0.01 and 100 times the value assumed for Jupiter, τ_J . We then repeated each of these simulations assuming three different planet obliquities, ψ_p : 0° , 90° , and 180° . Lastly, after running each model for 3.1 Gyr, we compare the final semimajor axis of the moon to the stability limit from dynamic simulations to determine whether tidal migration can significantly destabilize the system. The results of this experiment are shown in Figure 2.4.

2.3 Results and Discussion

In this section, we discuss the results of our numerical N -body and tidal migration simulations. We then discuss the observability of large exomoons orbiting HIP 41378 f in transit photometry by comparing theoretical finely sampled light curves to observations from HST and K2 and simulating idealized observations from the PLANetary Transits and Oscillation of stars (PLATO) mission. Finally, we explore the potential impact of large moons with atmospheres on the observed transmission spectrum of HIP 41378 f.

Stability Limits from Dynamical Simulations

Our three-body simulations complement the dynamical work of Rosario-Franco et al. (2020) and explore the HIP 41378 system in greater detail. While Rosario-Franco et al. (2020) studied the stability of a Neptune-size moon orbiting a Kepler-1625b analog as a function of planet eccentricity and moon semimajor axis, here we simulated HIP 41378 f with a $0.15 M_\oplus$, Mars-size satellite,

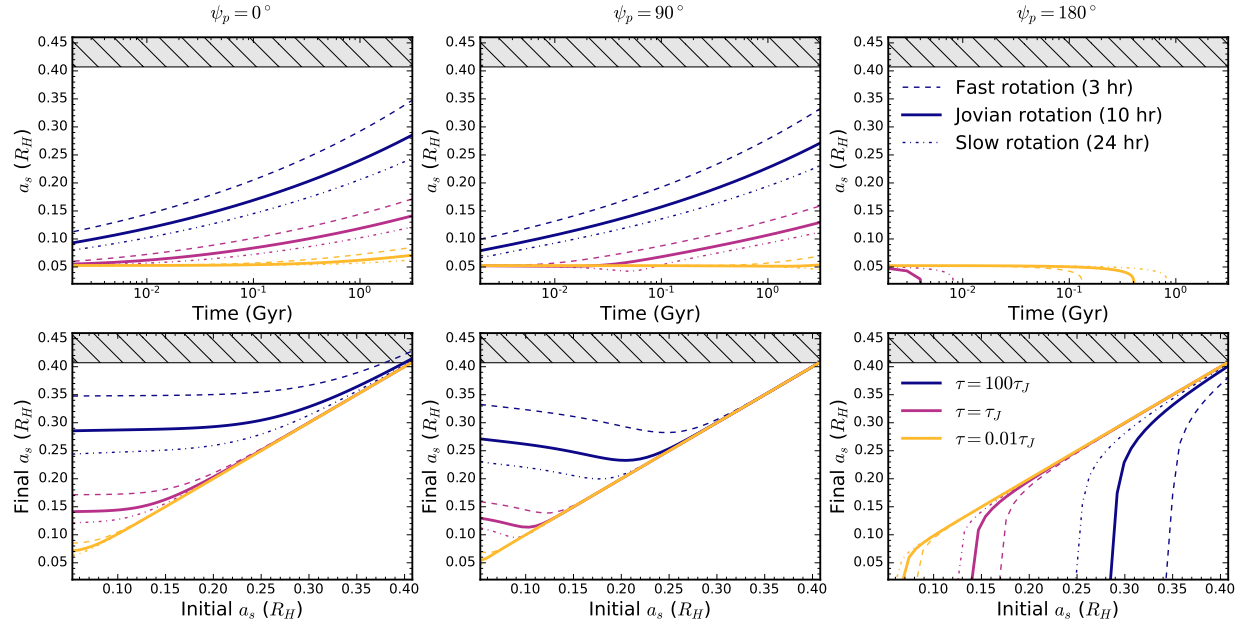


Figure 2.4: Equilibrium tide evolution models for a $0.15 M_{\oplus}$ ($0.53 R_{\oplus}$) satellite orbiting HIP 41378 f computed with the CTL mode in EqTide (Barnes 2017) for different planet obliquities. Top row: Moon semimajor axis as a function of time over the lifetime of the system, starting from an initial orbital separation of $4R_p$. Bottom row: Final vs. initial moon semimajor axis after 3.1 Gyr, the estimated age of the system (Santerne et al. 2019). The columns from left to right show the results for different assumed planet obliquities (moon inclinations): $\psi_p = 0^\circ$ (aligned prograde orbit), $\psi_p = 90^\circ$ (polar orbit), and $\psi_p = 180^\circ$ (aligned retrograde orbit). Each model assumes a different constant time lag τ for the planet, indicated by color (where $\tau_J = 0.00766$ s is roughly the value for Jupiter). The fiducial planet rotation period is assumed to be 10 hr (solid lines), but we also consider a slow rotation case ($P_{\text{rot}} = 24$ hr; dashed lines) and a fast rotation case ($P_{\text{rot}} = 3$ hr; dotted–dashed lines). The gray hatched regions highlight regions where the moon tends to become dynamically unstable, $a_s \gtrsim 0.41 R_H$ (see Figure 2.1). Note that the ratio of the final-to-initial moon semimajor axis approaches unity as the starting semimajor axis increases in each obliquity case we considered. This is consistent with the very strong dependence of τ_{mig} on the semimajor axis in Equation (2.9) for the zero-obliquity case (i.e., $\tau_{\text{mig}} \propto a^8$). Note also that for the retrograde ($\psi_p = 180^\circ$) case, moons with initial orbits close to the planet tend to migrate inward and ultimately collide with the planet, depending on the assumed planetary rotation and tidal lag constant.

varying the semimajor axis, a_s , inclination, i_s , and initial mean anomaly, $\mathcal{M}_s$, of the satellite. Ignoring the other planets in the system and assuming a fixed eccentricity of 0.035 (95% confidence upper limit; Santerne et al. 2019) for planet f, we defined the quantity f_{stab} as the fraction of 25 simulations within each quadtree grid cell that are stable over 10^5 yr. Figure 2.1 shows the results of our simulations, where f_{stab} is quantified by color.

From the benchmark three-body simulations described in Appendix 2.A, the outer stability limit for a satellite on a co-planar orbit around a planet with an eccentricity of 0.035 is $a_{\text{crit}} \approx 0.39R_H$. Our results shown in Figure 2.1 indicate that this limit depends only weakly on the inclination of the satellite for $\cos i_s \lesssim 0.8$. At higher inclinations, however, Kozai–Lidov oscillations can play a significant role in the dynamical evolution of the system, forcing the destabilization of the satellite over time. For these high-inclination systems, a trade-off can occur between the satellite’s inclination and eccentricity in order to conserve angular momentum, such that initially circular orbits become highly eccentric over time (i.e., bringing the satellite’s pericenter distance closer to the planet, and the apocenter distance farther away). As shown in Figure 2.1, this process starts to become important for $\cos i_s \gtrsim 0.8$ and dominates for $\cos i_s \gtrsim 0.95$ where there are no stable orbits.

The likelihood of these different inclination scenarios occurring in nature depends strongly on the formation pathway of the hypothetical moon. For moons formed within a circumplanetary disk, as is thought to be the case for the Galilean moon system around Jupiter, the inclination of the moon system relative to the planet’s spin axis should be low because of momentum conservation from the rotating circumplanetary disk. However, other formation scenarios, such as a kinetic impact or dynamical capture, may produce moons with more misaligned inclinations, which we have shown are less stable over long timescales, especially for closer-in orbits. We note, however, that tidal interactions may lead to significant outward migration of such close-in moons, thereby increasing their overall stability. The effects of tidal migration are discussed in greater detail in later in this section.

We then used the results from this three-body case and from our benchmark test in Appendix 2.A to inform our second set of simulations, which more realistically represent the HIP 41378 system with the inclusion of planet e. As the observed orbit of planet f is nearly circular, for each simulation we randomly selected the initial semimajor axis of its satellite from a uniform distribution between $0.1R_H$ and $0.4R_H$, the approximate stability limit for low-eccentricity planet orbits. The mass of the satellite was assumed to be the same as in our initial simulations ($0.15 M_\oplus$), and the initial mean anomaly and inclination were drawn from uniform distributions. The other initial parameters for the satellite and planets e and f were chosen randomly from the distributions given in Table 2.2. As before, we determined f_{stab} by taking the fraction of 25 simulations within a given quadtree cell spanning $\{e_e\}$ and $\{P_e\}$ that survived over 10^5 yr. Our results are shown in Figure 2.3, where again f_{stab} is indicated by color. We also show the upper limit on e_e as a function of P_e (given by Equation (2.2)), which is constrained by the (assumed fixed) orbit of planet d; and the observed values of e_e and P_e from Santerne et al. (2019).

The quasi-stable regions (left of the blue dashed line in Figure 2.3) are dominated by at least two independent effects. First, a trend of decreasing quasi-stability toward larger e_e is set by gravitational interactions between planet e and planet f’s satellite. At higher eccentricities, the

apastron distance of planet e becomes larger, reducing the separation between its orbit and the orbit of planet f. Therefore, when planet e has a high eccentricity, there is a greater likelihood that it will gravitationally perturb planet f’s satellite, leading to an unstable system. By the same physical reasoning, we also see a trend of decreasing quasi-stability along the period axis—for fixed eccentricity, the system becomes less stable as the period of planet e increases. In this case, the apastron distance also increases with period, according to Kepler’s third law, which again subsequently increases the likelihood of planet e gravitationally perturbing planet f’s satellite.

Second, the quasi-stable regions in Figure 2.3 are also influenced by the randomly distributed parameters in each simulation, which are independent of the orbit of planet e. These manifest as random noise in the stability map. For example, in cases where the mass of planet f is $\gtrsim 2\sigma$ less than the “best-fit” measured mass, the planet’s Hill radius becomes sufficiently small such that moons with larger initial orbital separations can more easily be stripped away. Moreover, moons that start out with orbits highly inclined to the reference plane of the planet (especially those with smaller semimajor axes) are more likely to be unstable due to Kozai–Lidov oscillations.

Because the observed period and eccentricity of planet e reside in a transitional quasi-stable region of the map, we cannot robustly conclude whether a moon orbiting planet f could be stable given the uncertainties in planet e’s measured period and eccentricity. Nonetheless, improved measurements of planet e’s orbit may yet reveal that the system actually resides in a stable region of Figure 2.3, for instance, if its eccentricity is determined to be smaller than currently constrained. If this turns out to be the case, then we would expect that most moons within $\sim 0.4R_H$ of planet f should remain stable as long as their orbits are not highly inclined relative to the planet’s reference plane. This result highlights the importance of modeling gravitational effects from other planets in multiplanet systems in the context of exomoon stability (and by extension, habitability), as well as the need for improved radial velocity measurements to measure planet masses in multiplanet systems.

Limits from Tidal Evolution

Tidal forces between two rotating bodies can lead to secular changes in their rotation and orbits. For example, a well-studied case in our solar system is the gradual recession of Earth’s Moon (and subsequent lengthening of the Earth’s day) over Gyr timescales. We investigated how such tidal migration may influence the long-term orbital stability of a hypothetical moon orbiting HIP 41378 f.

In our ET simulations outlined in Section 2.2, the secular evolution was parameterized by two intrinsic properties of the orbiting bodies, k_2 and τ . Though both k_2 and τ are completely unknown for HIP 41378 f (as are the moment of inertia and spin rate), there are constraints on these parameters for many solar system bodies (though τ and Q have uncertainties spanning multiple orders of magnitude). We therefore assumed that the properties of HIP 41378 f and any hypothetical moon are analogous to solar system bodies. As the fiducial case, we assumed Jupiter-like values for k_2 , τ , r_g , and Ω for the planet, as described in Section 2.2. We subsequently tested cases where τ was 2 orders of magnitude larger and smaller than the estimated Jovian value (with the larger value representing a planet with Neptune-like properties; e.g., Tokadjian and Piro 2020), and the rotation period was changed to either 3 hr (“fast”) or 24 hr (“slow”). Finally, we tested the effect of planet

obliquity by repeating our simulations for $\psi_p = 0^\circ$, $\psi_p = 90^\circ$, and $\psi_p = 180^\circ$. For the satellite, we assumed tidally synchronous rotation and k_2 , τ , and r_g consistent with rocky solar system bodies.

For simplicity, we assumed that each simulated moon started out with a circular orbit. We ran each simulation for 3.1 Gyr, varying the initial semimajor axis of the moon from $4R_p$ ($\approx 0.0525R_H$) to $30.5R_p$ ($\approx 0.4R_H$) such that the moon's initial orbital period was always longer than the planet's rotation period. This was to ensure that no inward migration would occur for prograde satellites, in which the moon could ultimately collide with the planet (e.g., for the 24 hr rotation case, the moon would migrate inward instead of outward if its semimajor axis were $\lesssim 1.6R_p$). For each rotation rate, constant time lag, and obliquity case, we show an example of the time evolution of the satellite's semimajor axis in Figure 2.4, as well as how the final semimajor axis of the satellite varies as a function of its initial semimajor axis.

Our results demonstrate that tidal migration should not significantly alter the stability of a moon orbiting HIP 41378 f over the system's lifetime, except if the moon is in a retrograde orbit relative to the planet's spin ($\psi_p = 180^\circ$) or if τ or Ω of the planet is very large. In the former scenario, the moon can be forced to migrate inward sufficiently to collide with the planet, depending on the assumed tidal parameters and the planet's rotation rate (outward migration is not allowed here, so these results are independent of the N -body stability limit). Note that for the $\psi_p = 90^\circ$ case, some inward migration may occur depending on the initial conditions, but not sufficiently to cause a collision. However, as we demonstrated with our N -body simulations, Kozai–Lidov oscillations play a significant role in the dynamical stability of high-inclination orbits. In fact, we expect that Kozai–Lidov oscillations would not permit a stable polar orbit ($\psi_p = 90^\circ$) scenario to begin with. We also note that we did not self-consistently capture the full dynamics of the system here. In reality, we would expect both secular tidal migration and Kozai–Lidov oscillations to affect the stability of exomoons in a coupled way. It is beyond the scope of our work here to self-consistently model both tides and orbital dynamics simultaneously.

For the prograde orbit case ($\psi_p = 0^\circ$), because the secular evolution of the moon's semimajor axis determines whether the moon can remain dynamically stable, it is useful for our discussion to introduce a timescale associated with the evolution of a , which we can write as $\tau_{\text{mig}} \sim a/\dot{a}$ (where $\dot{a}$ is the first time derivative of a).

Under the assumptions that $\psi_i = e = 0$, $M_f \gg M_s$, and $\Omega_s/n = 1$ (i.e., the moon is tidally locked), we can use the time derivative from Equation (2.4) to show that the migration time scales as:

$$\tau_{\text{mig}} \propto \frac{a^8}{k_{2,p}\tau_p M_s R_p^5} \left(\frac{\Omega_p}{n} - 1 \right)^{-1}, \quad (2.9)$$

where the subscript “p” indicates the planet (primary) and subscript “s” indicates the satellite (secondary). Note that in Equation (2.4), the assumption of setting $e = 0$ implies that the $\beta(e)$, $f_1(e)$, and $f_2(e)$ terms become unity.

This scaling relation is consistent with our numerical results shown in Figure 2.4 for $\psi_p = 0^\circ$: larger values of τ cause the semimajor axis to increase on faster timescales than smaller values of τ , and shorter planet rotation periods (larger Ω) also lead to faster evolution of the semimajor axis. Therefore, we note that tides could potentially destabilize a moon with a prograde orbit if the

planet has a very large τ value (small Q) or is rotating quickly, which could increase the semimajor axis sufficiently after 3.1 Gyr to be beyond the empirically determined stability limit (see the blue dashed line in the right panel of Figure 2.4). In fact, if τ is sufficiently large, any moons that formed close to the stability limit could migrate outward far enough to be stripped away from the planet by dynamical interactions. This scenario would require that τ be roughly 2 orders of magnitude larger than the value estimated for the solar system giants. However, we cannot rule out this possibility because τ remains virtually unconstrained, especially for planets like HIP 41378 f, whose structure remains unknown with current measurements, and for which we have no close analogs in the solar system.

Furthermore, we can gain insights to different moon scenarios from the scaling relation in Equation (2.9). For example, this relation shows that less massive moons (which are presumably more common than the large moon we simulated here) migrate on a longer timescale, which means they would be less likely to be stripped away by dynamic interactions. Additionally, if HIP 41378 f has a smaller radius than assumed here, then the migration timescale could drastically increase as well ($\tau_{\text{mig}} \propto R_p^{-5}$). This could be the case, for example, if HIP 41378 f is indeed a smaller-sized planet surrounded by optically thick circumplanetary rings (although modeling such a scenario is beyond the scope of this work). This demonstrates that the cases we have chosen to simulate here probe near the upper limit of plausible moon configurations: decreasing the mass of the moon or shrinking the size of the planet would only serve to increase the chances of the moon’s survival.

Exomoon Observability

Despite significant challenges in robustly detecting moons orbiting exoplanets, a number of efforts in recent years have attempted to uncover the first exomoon signals. Notably, the “Hunt for Exomoons with Kepler” (HEK; Kipping et al. 2022) systematically analyzed the light curves of a subset of all Kepler planet candidates most amenable to hosting a moon. Using Bayesian multimodal nested sampling with a photodynamical forward model (LUNA; Kipping 2011) to generate combined planet–moon transit light curves, Kipping et al. (2013b) constrained the satellite-to-planet mass ratios for seven potential satellite-hosting exoplanets, but did not find strong evidence for an exomoon around any. Subsequent HEK searches also resulted in null exomoon detections in dozens of Kepler systems (Kipping et al. 2015), but set upper mass limits on satellites orbiting the habitable-zone planet Kepler-22b (Kipping et al. 2013a) in addition to eight planets in M-dwarf systems (Kipping et al. 2014). HEK has also constrained a tentative upper limit on the occurrence rate of Galilean-size moons around planets orbiting between 0.1 and 1 au (Teachey et al. 2018).

Although these surveys have not yet robustly confirmed any exomoons, they have detected at least two exomoon candidates. Teachey and Kipping (2018) reported evidence from transit observations and timing variations of the first exomoon candidate Kepler-1625b I, consistent with a Neptune-size satellite orbiting a Jovian-like planet. More recently, Kipping et al. (2022) found tentative evidence supporting the existence of the exomoon candidate Kepler-1708b I, consistent with a $2.6 R_{\oplus}$ satellite. However, the veracity of either detection is the subject of ongoing discussion in the literature (e.g., Kreidberg et al. 2019; Teachey et al. 2020; Cassese and Kipping 2022).

Based on a suite of N -body and ET simulations in this work, we have shown that it is feasible for HIP 41378 f to host a relatively large exomoon. Naturally, this leads to the question of whether such a moon could be detected with current or future facilities. While direct photodynamical searches for exomoons may be promising for other systems (e.g., Kepler-1625b and Kepler-1708b; Teachey and Kipping 2018; Kipping et al. 2022), several factors inhibit such an effort for HIP 41378 f given existing data and the properties of the system.

For example, unlike the original Kepler mission, the extended K2 mission experienced significant systematic noise correlated with the spacecraft pointing (Howell et al. 2014). Though it is possible to correct some correlated noise algorithmically (e.g., Vanderburg et al. 2016b), residual systematics can persist at levels comparable to an exomoon signal. Stellar granulation and p-mode oscillations may also persist as relevant noise sources. Moreover, for HST observations, systematic noise and gaps in phase coverage introduced by the observatory’s orbit must be treated with caution, as these effects may also complicate detecting an exomoon in precise photometry (e.g., Kreidberg et al. 2019). For multiplanet systems such as HIP 41378, one must also be cautious of additional uncertainties in the inferred masses and orbits of sibling planets in the system (e.g., planet e), which can in turn lead to TTV uncertainties that affect the exomoon host. Without a firm grasp of the planet–planet-induced TTVs in the system, it is prohibitively difficult to disentangle potential TTVs caused by an orbiting exomoon, though in principle it may be possible for other systems (Kipping 2021).

While these factors preclude a meaningful direct photodynamical search for exomoons orbiting HIP 41378 f with current observations, it is still worth considering the effects that a large exomoon may have on transit observations. Although it is currently very difficult to detect exomoons (and robust confirmation is even more challenging), these objects are almost certainly included in observations of their exoplanet hosts. As observations become more precise with newer technology (e.g., JWST and ELTs) it may be necessary to consider exomoons as a potential source of correlated noise when interpreting observations of exoplanets, especially in the case of investigating atmospheres of smaller planets in the search for biosignatures. In the following sections we consider an idealized analog of HIP 41378 f to explore how large exomoons could affect precise transit observations.

HST White Light Curve

To demonstrate the high signal-to-noise ratio required to detect a transiting exomoon, we modeled the fully detrended HST white light curve of HIP 41378 f from Alam et al. (2022) and injected signals from hypothetical moons orbiting the planet. We computed model light curves and evaluated the likelihood of each model using the Pandora package (Hippke and Heller 2022), an open-source photodynamical exomoon transit code optimized for computational speed and accuracy. First, for the planet-only model, we fixed the barycentric orbital period, semimajor axis, and inclination to the current literature values for HIP 41378 f (Santerne et al. 2019), and fit for the planet-to-star size ratio R_p/R_* , quadratic limb-darkening coefficients q_1 and q_2 (Kipping 2013), and an offset ΔT_0 in the barycentric time of transit center T_0 to allow for small deviations from the transit center reported in Alam et al. (2022). We assumed a circular orbit for the planet. To compute the planet-

only model using Pandora, we fixed the satellite mass and radius to negligible values (see Hippke and Heller 2022).

Then, to derive posterior probability distributions for the planet-only fit, we used the nested sampling Monte Carlo algorithm *MLFriends* (Buchner 2016, 2019) implemented in the *UltraNest* package⁸ (Buchner 2021). We imposed a Gaussian prior on R_p/R_* based on the results of Alam et al. (2022), and a conservative uniform prior on ΔT_0 of ± 0.1 days.⁹ For the limb-darkening coefficients, we estimated initial values with the *ExoTiC-LD* package (Wakeford and Grant 2022) using the 3D stellar models from Magic et al. (2015) and stellar parameters from Santerne et al. (2019), then used these values to define Gaussian priors on q_1 and q_2 with standard deviations of 0.1. Using a Gaussian likelihood function, we then ran the *ReactiveNestedSampler* with 800 live points, and a step sampler with 2000 steps, until convergence was achieved. We chose this particular nested sampling approach because it can be easily extended to conduct efficient retrievals of the full set of planet and moon parameters, where the posterior probability distributions can be multimodal (see Hippke and Heller 2022). Figure 2.5 shows the detrended white light curve from Alam et al. (2022) along with the best-fit transit model from our nested sampling analysis. The full posterior probability distributions from the analysis are shown in Figure 2.B1 in this chapter’s appendix.

To investigate how a transiting exomoon would change the white light curve, we then calculated Pandora transit models with hypothetical $0.53 R_\oplus$ and $1 R_\oplus$ satellites injected on an arbitrary 30 day orbit ($a_s \approx 11 R_p \approx 0.14 R_H$) around HIP 41378 f. We calculated these models with Pandora assuming the best-fit parameters determined from the planet-only fit, but we set the moon radius to $0.53 R_\oplus$ or $1 R_\oplus$. In both cases, we arbitrarily selected the moon’s orbital phase for ease of comparison and ignored the TTV caused by the moon by leaving the satellite mass set to be negligible. For comparison, these moon-injected transit models are shown along with the best-fit planet-only model in Figure 2.5. The light curve models in Figure 2.5 clearly demonstrate the need for much higher precision ($\lesssim 15$ ppm) than is available in current HST observations in order to photometrically detect exomoons around HIP 41378 f.

We note that an independent analysis of the HST/WFC3 transit of HIP 41378 f obtained an rms in the HST transit light curve of 125 ppm (Edwards et al. 2023), compared to the 485 ppm rms obtained by (Alam et al. 2022). This level of precision is still $\gg 15$ ppm, so our conclusions here are independent of the choice of HST reduction. This high level of precision could, however, be within reach of JWST for certain systems. For example, Coulombe et al. (2023) showed that the JWST NIRISS/SOSS white light curve of WASP-18b bins down to ~ 5 ppm over 1 hr timescales, and Lustig-Yaeger et al. (2023) demonstrated a similar result for LHS 475b using JWST NIR-Spec/BOTS.

For completeness, we repeated the above procedure using observations from Campaigns 5 and 18 of the K2 mission (Vanderburg et al. 2016a; Santerne et al. 2019), which were detrended with K2SFF (Vanderburg et al. 2016b). For each K2 light curve, we removed low-frequency variability by fitting a basis spline to the out-of-transit flux and dividing it out of the data (as in Berardo et al.

⁸<https://johannesbuchner.github.io/UltraNest/>

⁹Alam et al. (2022) reported a much smaller uncertainty in T_0 of about ± 0.002 days.

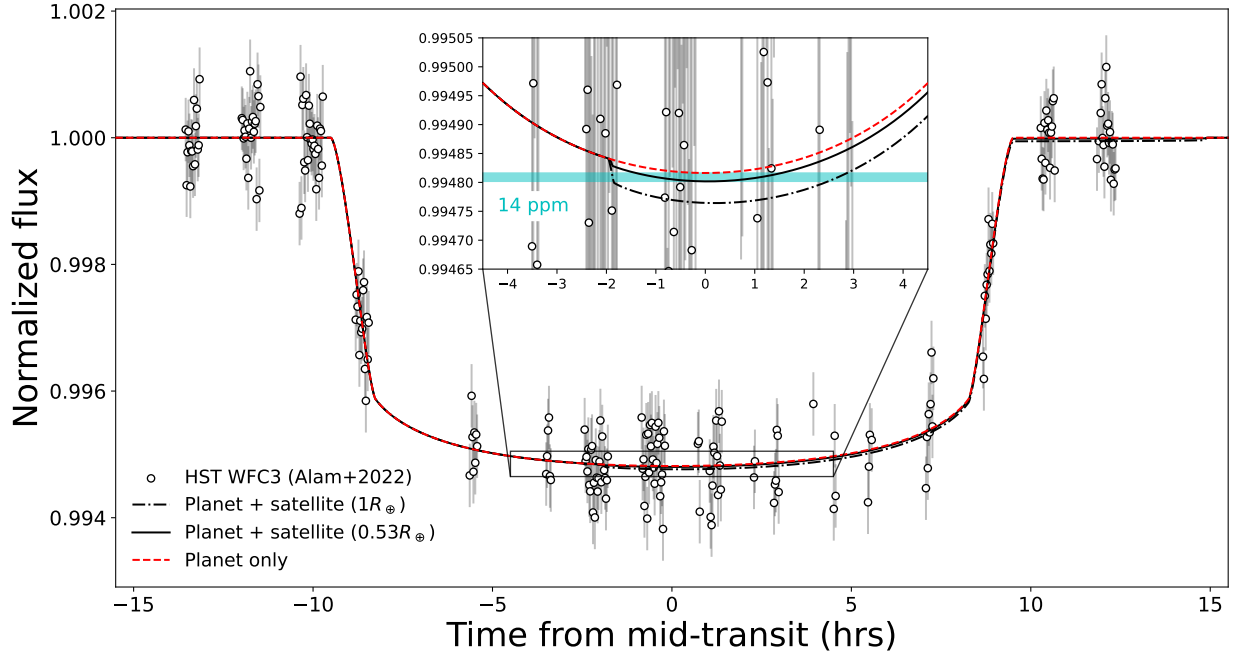


Figure 2.5: HST white light curve of HIP 41378 f from Alam et al. (2022) (points with error bars) and best-fit planet-only Pandora model (red dashed line). The black lines show simulated light curves with satellites injected at arbitrary orbital phases for ease of comparison. The solid line shows the signal from a $0.53 R_{\oplus}$ moon, while the dashed-dotted line shows the signal from an Earth-size moon. Both simulated moons are assumed to have orbits aligned with the planet’s reference plane and an orbital period of 30 days. A zoomed-in view near the transit center is shown in the inset panel, demonstrating the small effect produced by the presence of exomoons. The maximal flux difference between the moon-free and $0.53 R_{\oplus}$ moon models (~ 14 ppm; i.e., the transit depth of a $0.53 R_{\oplus}$ body transiting a $1.3 R_{\odot}$ star) is highlighted in cyan. Posterior distributions for the planet-only model parameters are shown in Figure 2.B1.

2019). We then repeated the procedure used to fit a planet-only model to the HST data, but we used the results from Santerne et al. (2019) to define T_0 and set Gaussian priors on the R_p/R_* , q_1 , and q_2 . The K2 data and best-fit planet-only model are shown in Figure 2.B2 in this chapter’s appendix, along with the light curves with injected hypothetical satellites with radii of $0.53 R_{\oplus}$ and $1 R_{\oplus}$. The posterior probability distributions for the planet-only fit are also shown in the appendix in Figure 2.B3. Much like the HST observations, the K2 data are not precise enough to distinguish between planet-only and planet-moon transit models, as residual systematics at the $\gtrsim 20$ ppm level can mimic the small signal produced by a moon.

Finally, we simulated an idealized single transit observation of HIP 41378 f from the future PLATO mission, expected to launch no earlier than 2026 (Rauer et al. 2014). We considered two scenarios: one in which only planet f transits a bright, photometrically quiet star with properties of HIP 41378, and one in which the planet is orbited by an Earth-size satellite with the same configuration as previously described. We assumed a cadence of 600 s (10 minutes), as is expected

be used for PLATO light curves, and a noise level of 20 ppm/hr for a $m_V \sim 9$ star in PLATO’s P1 sample (though this number will actually depend on the number of cameras used to observe the target). Ignoring astrophysical variability, we added white noise to our simulated Pandora light curves; the noise was randomly drawn from a Gaussian distribution with a standard deviation of 49 ppm (i.e., 20 ppm/hr scaled to a 10 minute cadence assuming Poisson noise). The transit models and simulated PLATO observations are shown in the bottom panel of Figure 2.B2 in this chapter’s appendix. Even in these idealized PLATO simulations, the photometric noise floor makes it exceedingly difficult to distinguish between the moon and no-moon scenarios, even in the absence of systematic uncertainties. Therefore, any variations on the order of 10 ppm due to instrumental and astrophysical systematics must be well understood in order to robustly constrain the presence of an exomoon from transit observations alone.

Implications for Transmission Spectroscopy

As observational capabilities continue to improve in the era of JWST and beyond, it is worth considering the extent to which exomoons may affect the observed wavelength dependence of transit depth, or transmission spectrum, of temperate and potentially habitable worlds. Current HST WFC3 observations of HIP 41378 f’s atmosphere are consistent with a featureless transmission spectrum ($\chi_r^2 \approx 1.05$; Alam et al. 2022).¹⁰ Given the low density of the planet, its flat spectrum could be explained by a variety of possible scenarios, including an extended hazy atmosphere, a high-metallicity clear atmosphere, or an optically thick ring system (e.g., Akisanmi et al. 2020). As these scenarios are all consistent with the observations, for simplicity we chose here to model HIP 41378 f as if it had a high-metallicity clear atmosphere, and then assessed how an exomoon with a substantial atmosphere would alter its transmission spectrum.¹¹

We computed model transmission spectra and evaluated the likelihood of each one using the PLATON package (Zhang et al. 2019, 2020). First, we calculated the model for the planet based on the results of Alam et al. (2022), assuming a $300\times$ solar metallicity atmosphere and an isothermal ($T = 294$ K) pressure–temperature (P – T) profile. Following Alam et al. (2022), we fit the model to the observed spectrum by binning the model predictions to the wavelength channels of the observations and performing a least-squares fit. Keeping all other parameters fixed, we fit for a constant vertical offset in $R_p/R_\star$ to preserve the shape of the spectrum. The observed spectrum and best-fit $300\times$ solar metallicity model are shown in Figure 2.6.

We then computed a model for the combined transmission spectrum of a planet and a moon, assuming bodies both have substantial atmospheres and are in an optimal transit geometry (i.e., we see the maximum contribution of a potential moon’s atmosphere). Following our stability

¹⁰Note that Edwards et al. (2023) reported a different transmission spectrum from an independent analysis of the HST/WFC3 data. We discuss this point later in this section.

¹¹We note that the high-metallicity clear atmosphere is not necessarily the most likely scenario for this planet, and its nature may in fact be some combination of the scenarios we have described (e.g., the planet could have rings and a moon, rings and hazes, rings and hazes and a moon, etc.). While in principle each of these scenarios could affect the observed transmission spectrum of the system in a unique way, it is beyond the scope of this paper to model each possible ring/haze/moon permutation.

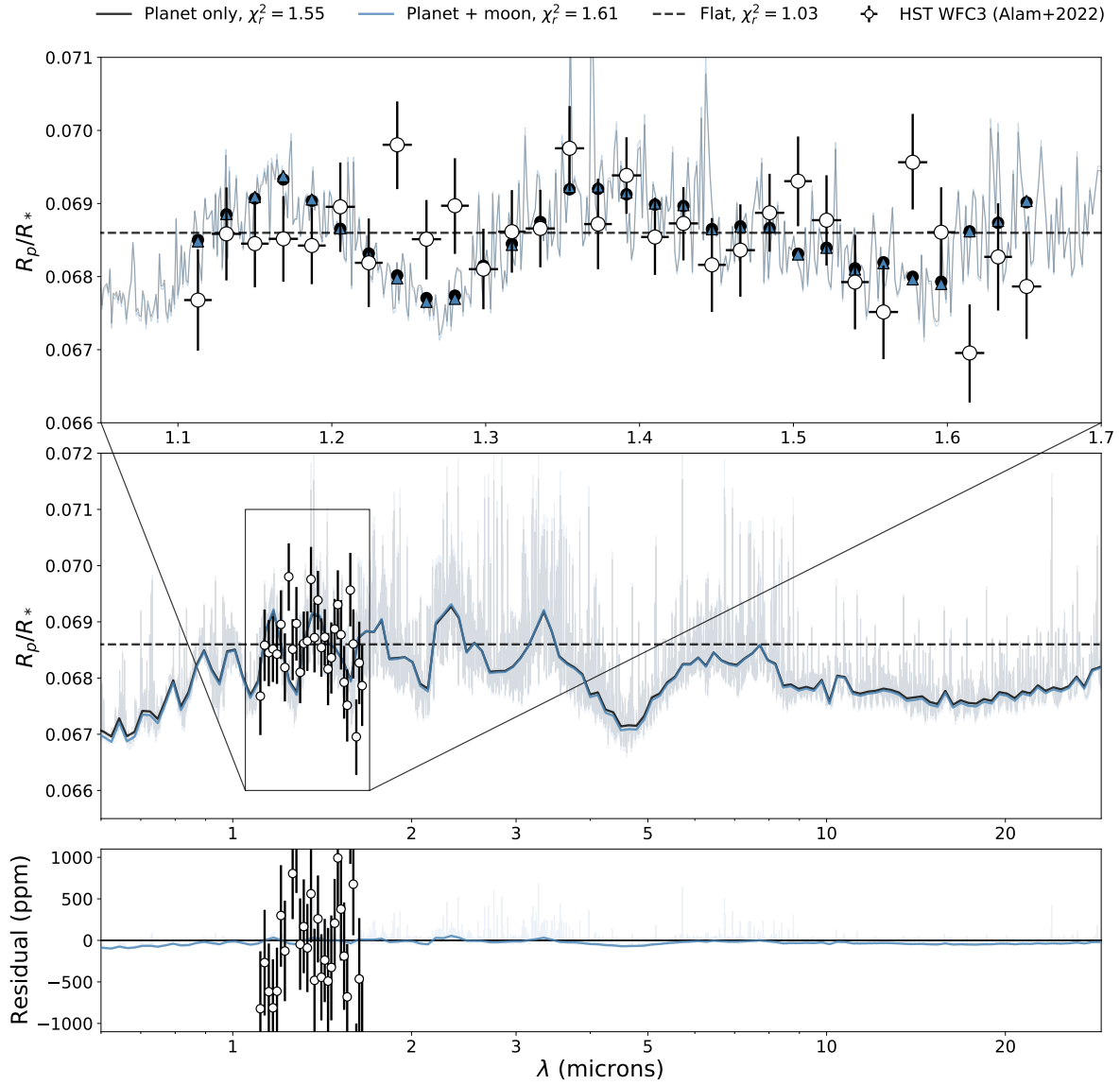


Figure 2.6: Top: Transmission spectrum of HIP 41378 f (points with error bars; Alam et al. 2022), compared to 1D atmospheric forward models and a flat line. For the planet-only model (black line), we assume a cloud-free $300\times$ solar metallicity atmosphere and an isothermal ($T = 294$ K) P - T profile; the combined planet and moon model (blue line) is described in the main text. The fainter lines show the computed unbinned ($R \sim 1000$) PLATON spectra, while the colored points show each model binned to the same resolution as the WFC3 observations. Middle: HIP 41378 f spectrum and models shown in the full PLATON wavelength range, including wavelengths that are accessible with JWST. The darker bold lines are binned by a factor of 30 to facilitate easier comparison. Bottom: Residual signal between the observed spectrum and the planet-only spectrum model, and between the planet-only spectrum model and the planet-moon model, over the same wavelength range.

simulations, we considered the scenario of a $0.53 R_{\oplus}$ ($0.15 M_{\oplus}$) moon. For the hypothetical moon, we assumed the same isothermal P – T profile but imposed a metallicity that would result in a maximally “puffy” atmosphere in order to explore an upper limit on the exomoon’s signal in the transmission spectrum.

We determined the lowest feasible atmospheric metallicity by considering the timescale associated with atmospheric boil-off due to an isothermal Parker wind (see, for example, Owen and Wu 2016; Wang and Dai 2019). We set the boil-off timescale, τ_{boil} , equal to the system age (~ 3.1 Gyr; Santerne et al. 2019), and solved for the mean molecular weight, μ , using the following set of equations:

$$\tau_{\text{boil}} \sim \frac{M_{\text{atmo}}}{\dot{M}_{\text{Parker}}}, \quad (2.10)$$

$$\dot{M}_{\text{Parker}} = 4\pi r_s^2 c_s \rho_0 \exp\left(\frac{3}{2} - \frac{2r_s}{R_{\text{sat}}}\right), \quad (2.11)$$

where r_s is the sonic radius, defined as $r_s = GM_{\text{sat}}/(2c_s^2)$; c_s is the isothermal sound speed, defined as $c_s = (kT/\mu)^{1/2}$, and ρ_0 is the atmospheric mass density at the surface (k is the Boltzmann constant).

Assuming a surface pressure of 1 bar for the $0.53 R_{\oplus}$ moon’s atmosphere (comparable to the atmospheric surface pressure on Titan), we found a minimum mean molecular weight of $\mu \sim 4.1$, approximately $2\times$ that of Jupiter and $1.5\times$ that of Neptune. This corresponds to a metallicity of approximately $120\times$ solar. We note, however, that this estimation is optimistic, as we do not consider other mass loss processes, such as photoevaporation. Importantly, we also note that we do not self-consistently model the moon’s atmospheric or interior structure, nor how the moon acquired an atmosphere with this composition in the first place. The results presented here are simply intended as a thought experiment for a maximally detectable exomoon, rather than a robust constraint on plausible exomoon atmospheres.

Under the assumption that the hypothetical moon would have had a viable formation pathway to achieve such a low-metallicity atmosphere, we computed its spectrum with PLATON and then combined this with the planet-only model as follows:

$$(R_p/R_{\star})_{\text{eff}} = \sqrt{\delta_p + \delta_s}, \quad (2.12)$$

where $(R_p/R_{\star})_{\text{eff}}$ is the effective planet-to-star radius ratio due to the planet and moon, and δ_p and δ_s are the wavelength-dependent transit depths due to the planet and moon, respectively. We then performed a least-squares fit to the observed spectrum from Alam et al. (2022), preserving the shape of the total spectrum by fitting only for a constant offset in $R_p/R_{\star}$. Both models are shown alongside the observations in Figure 2.6, along with the residual $R_p/R_{\star}$ between the planet-only and combined planet-moon models.

Qualitatively, the addition of a moon with a substantial atmosphere results in a superposition of the moon and planet transmission spectra. Given our assumptions, the main differences between the planet-only spectrum and combined planet-moon spectrum are slightly enhanced H_2O absorption features (< 50 ppm excess in $R_p/R_{\star}$) and a relative deficit in mid-IR and optical absorption

(< 100 ppm difference in R_p/R_*) for the combined planet and moon models. We quantified the quality of each model fit, along with a flat line fit, using the reduced least-squares statistic. We were unable to distinguish between the planet-only $300\times$ solar metallicity model ($\chi_r^2 \approx 1.55$) or the flat line ($\chi_r^2 \approx 1.03$) given the precision of the existing data, consistent with Alam et al. (2022). Rather unsurprisingly, the addition of the $0.53 R_\oplus$ exomoon with a $\mu \sim 4.1$ atmosphere is also indistinguishable compared to the planet-only model and the flat line ($\chi_r^2 \approx 1.61$). It is interesting to note that the independent analysis of Edwards et al. (2023) resulted in a different transmission spectrum from the HST/WFC3 data. Their final spectrum shows an upward slope from blue to red which is difficult to reproduce with equilibrium chemistry models and would lead to a qualitatively poorer fit to the forward models in Figure 2.6. Although we do not investigate the nature of the slope seen in Edwards et al. (2023), we note that using their spectrum would not change our inferences about the inability to detect an exomoon in the HST data.

Though the low-metallicity atmosphere we considered here is an extreme scenario and not necessarily likely for a moon orbiting HIP 41378 f, the excess absorption features in the model transmission spectrum may suggest that other systems containing large exomoons with thick atmospheres could experience nonnegligible contamination if observed at high enough precision. This would be especially important for planets with smaller radii than we considered here. Such observations would need to be capable of resolving ~ 10 ppm absorption features, a task that would be challenging even for JWST (e.g., Coulombe et al. 2023; Lustig-Yaeger et al. 2023).

For example, moons with substantial atmospheres could in principle contaminate high-fidelity spectra of terrestrial planets, introducing systematic uncertainties in possible detections of biosignature molecules. Moreover, the effects of a moon’s atmosphere could vary in time, as the orbital phase of the moon at the time of observation changes with each transit. The temporal variability of the combined spectrum could therefore be misinterpreted as an intrinsic signal in the atmosphere of the planet. Finally, the spectra of planets with large moons could be harder to interpret even if the moon itself lacks a substantial atmosphere, having an effect analogous to the transit light source effect (Rackham et al. 2018, 2019). In this case, a moon could create an apparent time-varying inhomogeneity on the disk of the host star, leading to contaminated spectral features. While the scenarios discussed here are only for individual large moons, the presence of multiple smaller moons (as in the outer solar system) could also introduce additional timescales and complexity to the problem. Therefore, it may be important to consider moons as a source of uncertainty in transmission spectroscopy as advances in technology allow for more precise measurements of exoplanet atmospheres.

2.4 Conclusion

In this work, we investigated the stability of a hypothetical large moon ($0.15 M_\oplus$, $0.53 R_\oplus$) orbiting the long-period $12 M_\oplus$ ($P \approx 1.5$ yr) planet HIP 41378 f. Using a suite of numerical N -body simulations, we have shown that moons up to this size can survive in the system over long timescales over a wide range of system setups, including with the added complexity of multiple planets in the HIP 41378 system and tidal interactions between the moon and the host planet. Although our

analysis has demonstrated the plausibility of a moon orbiting HIP 41378 f, we have shown that the detection of a relatively large Earth-size moon in the system is unlikely given current observations, but may be feasible in the near future with high-precision JWST or PLATO observations. Moreover, an exomoon with a sufficiently puffy atmosphere could imprint ~ 10 ppm features on the transmission spectrum of the planet, however it is unclear how this signal could be disentangled from planetary spectral features. Our main conclusions are summarized as follows:

1. HIP 41378 f could feasibly host exomoons at least as massive as $0.15 M_{\oplus}$ that are stable over a timescale of 10^5 yr, consistent with stability limits determined by previous work (e.g., Rosario-Franco et al. 2020). Under ideal assumptions of zero-eccentricity and co-planar orbits, a $0.15 M_{\oplus}$ moon does not escape the gravitational sphere of influence of planet f or collide with the planet as long as it orbits within $\sim 40\%$ of the planet’s Hill radius. Our simulations demonstrate that this limit does not depend strongly on $\cos i_s$ for most (low) moon inclinations. However, Kozai–Lidov oscillations can start to become an important destabilizing influence for $\cos i_s \gtrsim 0.8$, and disallow stable orbits for the highest inclinations ($\cos i_s \gtrsim 0.95$). The satellite mass chosen here represents an extreme scenario, analogous to the highest moon-to-planet mass ratio observed in the solar system.
2. Current constraints on the mass and orbit of the inner planet HIP 41378 e do not necessarily preclude the possibility of a moon orbiting planet f. However, improved measurements of both planets’ masses and orbits are needed to robustly constrain the stability of a putative exomoon in the system. If, for example, the true eccentricity of planet e is 1σ smaller than the eccentricity reported by Santerne et al. (2019), then moons orbiting within $\sim 40\%$ of the Hill radius of planet f should be stable, so long as $0 < \cos i_s \lesssim 0.9$. This not only highlights the need for improved masses and orbital constraints for the planets in the HIP 41378 system but also the importance of considering multiple planets in the dynamical modeling of exomoon stability in multiplanet systems in general.
3. For most circular prograde orbits, tidal interactions between planet f and a moon are not sufficient to cause the moon to migrate outward beyond the $0.4R_H$ dynamical stability limit, assuming that planet f has tidal response properties comparable to the solar system giant planets. However, under extreme circumstances where planet f is given a very large time lag ($\tau \gtrsim 0.7$ s) and fast rotation rate ($P \sim 3$ hr), tidal migration can lead to the moon’s escape from the gravitational influence of the planet. While in principle more massive moons would also migrate faster, we do not consider such cases here because moons with higher mass ratios have not been confirmed in the solar system or in extrasolar systems. For high planet obliquities (or moon inclinations), tidal interactions alone are not sufficient to destabilize the moon, but, as mentioned in the first point, Kozai–Lidov oscillations can become significant enough to destabilize such systems. We also note that moons with retrograde orbits are more likely to collide with the planet due to inward tidal migration (independent of the dynamical stability limit), but this depends strongly on the assumed tidal parameters of the planet, which remain unconstrained.

4. Existing observations of the HIP 41378 system from HST and K2 cannot reliably constrain the presence of exomoons, as the expected transit signal produced by a large moon ($0.53 R_{\oplus}$) is only on the order of 15 ppm. Furthermore, uncertainties in the orbits and masses of the planets in the HIP 41378 system, as well as correspondingly uncertain TTVs, would make the detection of a moon challenging with planned missions such as PLATO. However, it is possible that future observations with JWST capable of precision better than ~ 20 ppm on 10 minute timescales will be able to detect exomoons in other systems with more robust planet measurements. For example, the giant temperate planet PH-2b (Kepler-86b) will be observed by JWST NIRSpec/PRISM in GO Cycle 2 (Proposal ID: 3235; PI: Fortney), and could potentially provide serendipitous observations of a transiting exomoon.
5. Exomoons with thick atmospheres could contaminate the transmission spectra of exoplanets at the ~ 10 ppm level in a time-dependent manner (well below the precision of HST observations). However, this is an optimistic estimate which assumes that a moon can acquire and retain a low mean molecular weight atmosphere over its lifetime. Nonetheless, exomoons with significant atmospheres may be sources of uncertainty in other exoplanet systems as new technology enables smaller and smaller signals to be probed.

We note that while our analysis provides conservative limits on the stability of exomoons orbiting HIP 41378 f using well-tested methods such as N -body simulations and equilibrium tide modeling, there are a few caveats that may be important to consider in the real HIP 41378 system. For example, multiple planets in the system do not have well-constrained orbital periods or masses due to the difficulty of measuring long-period planets ($P \gtrsim 1$ yr). While we attempted to incorporate some of this uncertainty in our analysis (e.g., randomly drawing masses and orbital parameters for planet e in our N -body simulations), we could not account for all the unconstrained degrees of freedom in the actual HIP 41378 system, which includes at least 5 planets in total. Moreover, we did not attempt to model the effects of multiple moons in the system, which also would have increased the complexity of our simulations.

Given the current data, another caveat is the uncertainty surrounding the nature of the planet HIP 41378 f. Throughout our analysis, we assumed that the planet has a mass and radius consistent with recent observations (Santerne et al. 2019) and tidal properties similar to a solar system Jovian planet. However, if in reality the planet is more similar to Neptune and it possesses a circumplanetary ring system (e.g., Akisanmi et al. 2020; Piro and Vissapragada 2020), this could change the tidal response of the planet and therefore affect the orbital stability of moons.

Moreover, self-consistent modeling of any moon–ring interactions is beyond the scope of this work but would be an interesting subject of future simulations. Akisanmi et al. (2020) showed that observations of HIP 41378 f are consistent with a planet of radius $R_p = 3.7 R_{\oplus}$ ($\rho_p = 1.4 \text{ g cm}^{-3}$), with opaque rings extending from 1.05 to $2.6 R_{\oplus}$. If the rings extend out to the Roche radius, it follows that the density of the ring material would be $\rho_r = 1.08 \text{ g cm}^{-3}$. In this case, assuming that the ring particles have a typical radius of about 100 cm, the total mass of the rings would be approximately 10^{19} kg (see Equation (4) of Piro 2018b), roughly the observed mass of Saturn’s rings (Iess et al. 2019). Hence, in reality, gravitational interactions between the rings and the moon

may affect their long-term stability (e.g., Nakajima et al. 2020). On a similar note, we did not attempt to model the combined observable effects of moons and rings (Ohno and Fortney 2022).

Finally, throughout our analysis, we assumed that moons are a natural outcome of planet formation, and we only considered the stability of moons once they reached a tidally locked state with planet f. That is, we did not attempt to treat exomoon formation and evolution in a self-consistent manner, and we remained agnostic to the specific formation pathway of our simulated moons.

To assess the observability of an exomoon, we chose to model transit observations because these are likely the most promising for a long-period transiting planet like HIP 41378 f. We note that aside from photodynamical transit searches for exomoons such as HEK (Kipping et al. 2012) and the forthcoming Transiting Exosatellites, Moons, and Planets in Orion (TEMPO) survey (Limbach et al. 2023), several other methods of detecting exomoons have been proposed. For example, the orbital sampling effect (OSE) technique (Heller 2014), which leverages many transit observations to achieve robust statistics, can be used to infer the size, orbital separation, and mass of transiting exomoons from a phase-folded light curve of about a dozen transits (Hippke 2015; Heller et al. 2016). However, this is not currently feasible for HIP 41378 f because the planet’s long orbital period and transit duration make it difficult to acquire the necessary large number of observations.

Other novel approaches, including direct imaging and Doppler spectroscopy (Peters-Limbach and Turner 2013; Agol et al. 2015; Vanderburg et al. 2018), radio emission from satellite-hosting exoplanets (Noyola et al. 2014, 2016; Narang et al. 2023), and combined planet–moon thermal phase curves (Forgan 2017), may also be fruitful probes of exomoons with future technologies. But again, HIP 41378 f is not an optimal target for such studies. The semimajor axis of planet f is too small for current direct imaging technology, with a sky-projected angular separation of ~ 13 mas, and uncertainties in the other planet masses and orbits preclude a radial velocity exomoon search. Moreover, uncertainty regarding the nature of planet f makes radio emission studies challenging, and the cool equilibrium temperature of planet f ($T_{\text{eq}} = 294$ K) is not sufficient to produce an appreciable thermal phase curve.

Nonetheless, as our ability to measure exoplanets continues to improve in the future, exomoons may indeed become a more important source of systematic uncertainty (in addition to transit light source variability, stellar spectrum noise, etc.). Decades into the future, we may even be able to robustly confirm detections of exomoons and constrain the properties of their atmospheres with state-of-the-art observational facilities such as ground-based ELTs and next-generation space missions like the Habitable Worlds Observatory (HWO). For example, the Ancillary Science Case A-19 for the Large UV/Optical/Infrared Surveyor (LUVOIR) suggests spectroastrometry (i.e., measuring the astrometric shift that occurs between wavelengths with flux dominated by the exoplanet and wavelengths dominated by the exomoon) as a possible exomoon detection strategy with a 12 m class space telescope (The LUVOIR Team 2019). With contrast $> 10^{-9}$ and relative astrometric precision between wavelength bands of ~ 0.1 mas, such an observatory could in principle detect an Earth-size exomoon orbiting a 1 au Jupiter-size planet at 10 pc. Not only would this be a revolutionary discovery in itself, but it would also open the possibility of using exomoons as a way of studying planet formation and evolution, and even provide a potential new avenue for searching for signs of life beyond the solar system.

Appendix

2.A Benchmark Three-body Simulation

While in Section 2.2 we describe our N -body simulations for exploring how the semimajor axis and inclination of the satellite and the presence of planet e affect the system’s stability, here we describe the set of initial simulations that were used to test our N -body code.

We benchmarked our code by following the general procedure outlined by Domingos et al. (2006) and Rosario-Franco et al. (2020). We set up our grid of simulations using a quadtree data structure implemented in `astrQTPy` (Harada 2023), which we described in more detail in Section 2.2. We constrained the initial eccentricity, e_f , of planet f between 0.0 and 0.5, and the initial semimajor axis, a_s , of the satellite between 0.25 to $0.55R_H$, where R_H is the Hill radius defined in Equation (2.1) ($R_H \approx 0.03 \text{ au} \approx 76R_p$). These limits were chosen in order to explore the parameter space encompassing the stability limit determined by Rosario-Franco et al. (2020). Note however that the measured eccentricity of planet f is actually constrained to $e_f = 0.004^{+0.009}_{-0.003}$ (Santerne et al. 2019), as stated in the main text. As in Section 2.2 the planet and satellite were initialized with co-planar orbits, with the longitudes of the ascending node and arguments of pericenter set to zero ($\Omega = \omega = 0^\circ$), and the mean anomaly of the planet set to zero ($\mathcal{M}_f = 0^\circ$).

We proceeded by dividing the parameter space evenly into a 4×4 grid and running 25 independent N -body simulations in each grid cell with (e_f, a_s) and the satellite mean anomaly, $\mathcal{M}_s$, drawn from uniform distributions. We calculated the fraction of stable systems, f_{stab} , in each cell as the fraction of simulations (out of 25) which satisfied the stability criteria defined in Section 2.2 over a timescale of 10^5 yr . We then continued splitting each grid cell in the quadtree into four equal child cells and computing more N -body simulations, following the procedure described in Section 2.2. Figure 2.A1 shows the final stability grid generated by our simulations, where f_{stab} is quantified by color. Regions where $0 < f_{\text{stab}} < 1$ are considered quasi-stable, while regions where $f_{\text{stab}} = 1$ ($f_{\text{stab}} = 0$) are absolutely stable (unstable) over 10^5 yr .

Our results were qualitatively similar to Rosario-Franco et al. (2020) and quantitatively consistent in terms of the stability boundary for low-eccentricity orbits (i.e., the largest value of a_s for a given e_f where $f_{\text{stab}} = 1$). Rosario-Franco et al. (2020) modeled the stability boundary as

$$a_{\text{crit}} = c_1(1 - c_2 e_f), \quad (2.A1)$$

where a_{crit} is implicitly in terms of the fraction of the Hill radius, c_1 is the stability limit for circular orbits, and c_2 is a slope parameter.

From their N -body simulations, Rosario-Franco et al. (2020) determined that $c_1 = 0.4061 \pm 0.0028$ and $c_2 = 1.1257 \pm 0.0273$. Their stability limit is shown in Figure 2.A1 plotted over our stability. Our results are in good agreement for low eccentricities, with our stability limit for circular orbits being $a_{\text{crit}} \approx 0.41R_H$. However, we note that our simulations tend to predict a slightly higher stability limit as eccentricity increases (for $e_f \gtrsim 0.15$). This discrepancy at higher eccentricities is likely due to our different choice of planetary semimajor axis; we assumed a semimajor axis of 1.37 au for HIP 41378 f, whereas Rosario-Franco et al. (2020) assumed an orbital

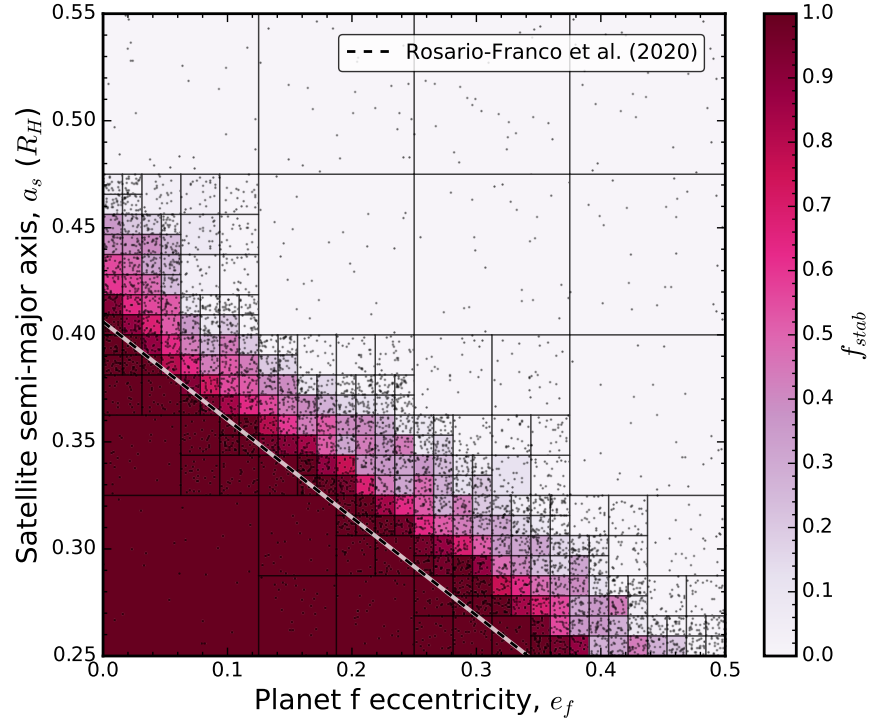


Figure 2.A1: Three-body orbital stability map for a system consisting of HIP 41378, planet f, and planet f’s satellite, as a function of planetary eccentricity, e_f , and satellite semimajor, axis a_s (expressed in terms of the Hill radius, R_H). The color of each grid cell corresponds to the fraction f_{stab} of 25 simulations within each cell (indicated by the black points) that survive over 10^5 yr. The stability limit determined by Rosario-Franco et al. (2020), shown as the dashed line, indicated good agreement with our simulations at low eccentricities.

separation of 1 au in their simulations. Because our simulated planet and its moon are farther away from the host star, the system tends to be more stable against gravitational perturbations.

2.B Additional Figures

Here we present additional figures that supplement the main text. Figure 2.B1 shows the posterior distributions derived from our nested sampling analysis of the HST white light curve shown in Figure 2.5. Figure 2.B2 shows additional photometric observations of HIP 41378 f from K2 Campaigns 5 and 18, along with simulated data of a single transit event from the upcoming PLATO mission. The posterior distributions derived from nested sampling analyses of the K2 light curves are shown in Figure 2.B3.

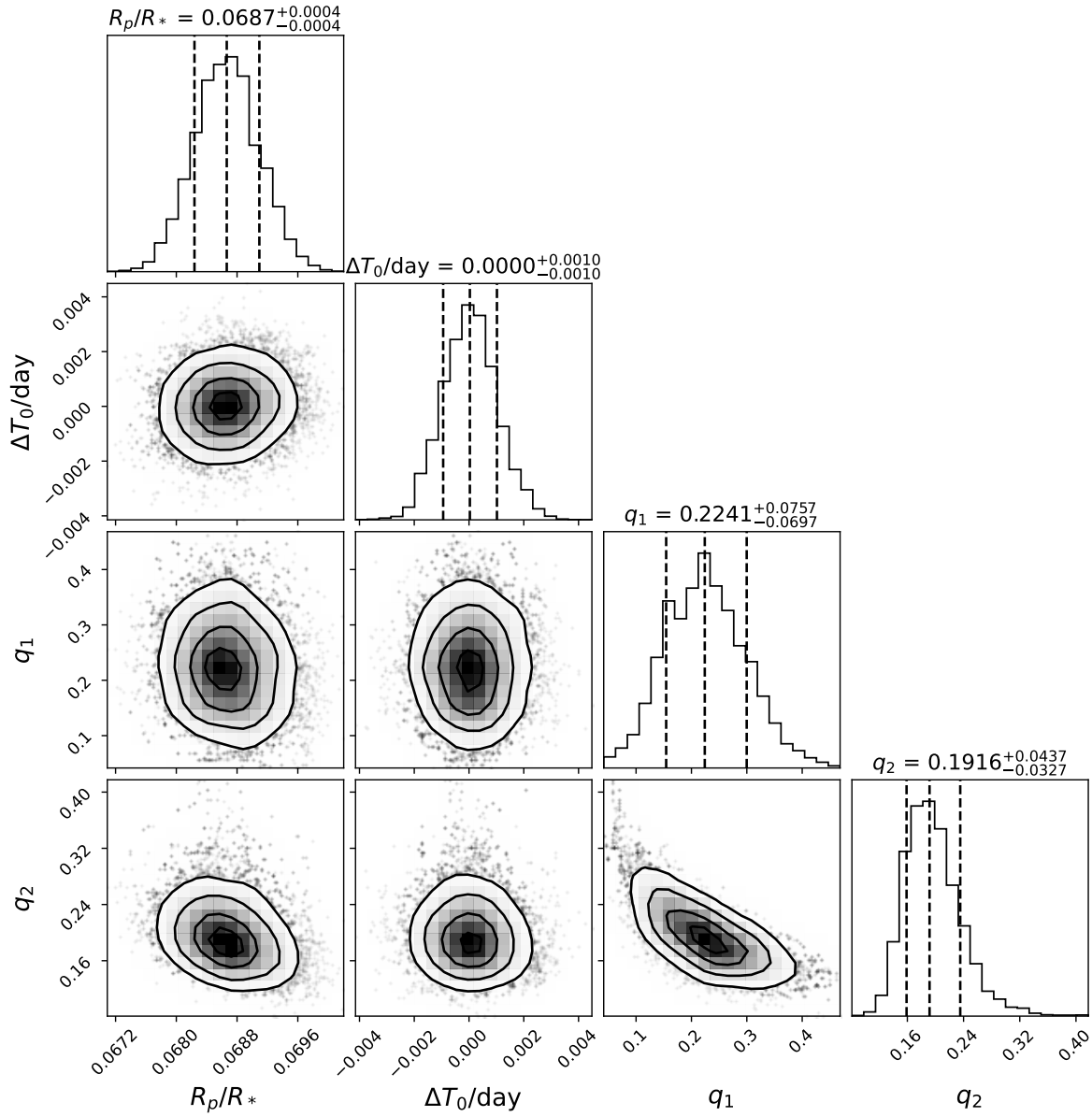


Figure 2.B1: HST white light curve posterior distributions for the planet-only model shown in Figure 2.5.

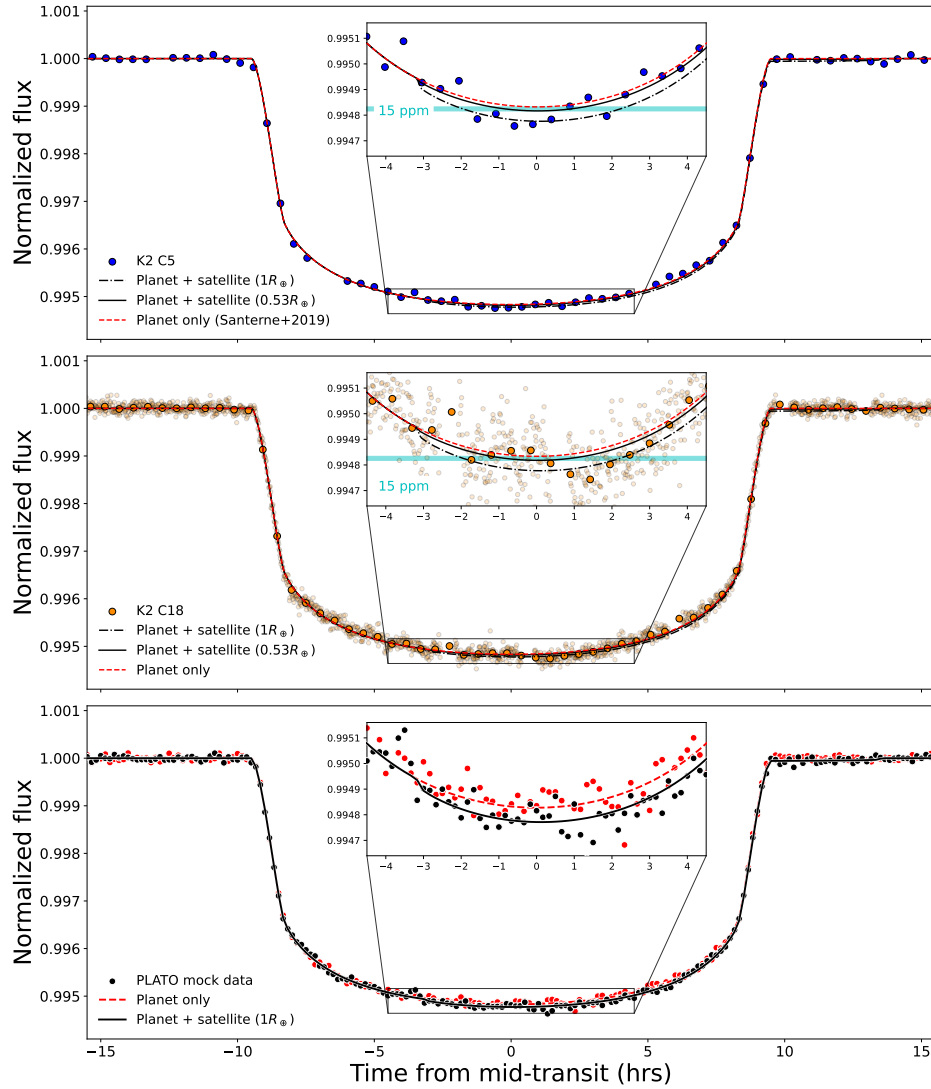


Figure 2.B2: Top: K2 transit light curve for HIP 41378 f from Campaigns 5 (blue points) and 18 (orange points) with best-fit planet-only model (red dashed line). As in Figure 2.5, additional models with injected signals from a $0.53 R_{\oplus}$ moon and an Earth-size moon are shown by the black solid line and dashed-dotted line. The inset panel shows a zoomed-in view near mid-transit, demonstrating that the effects of moons are below the noise level of the data. Note that the 15 ppm difference in mid-transit flux between the moon-free and $0.53 R_{\oplus}$ moon cases is slightly greater in the K2 bandpass than the HST bandpass (Figure 2.5) due to differences in the stellar limb-darkening coefficients. Middle: Same as the top panel, but with data from K2 Campaign 18. Short-cadence data are shown by the transparent points, while the opaque points have been binned to match the long-cadence data. Bottom: Simulated 10 minute cadence PLATO data for a single transit of HIP 41378 f assuming the presence of no moon (red points) and an Earth-size moon (black points). The underlying Pandora models for each case are shown by the lines with corresponding colors, and a zoomed-in view near mid-transit is shown in the inset panel.

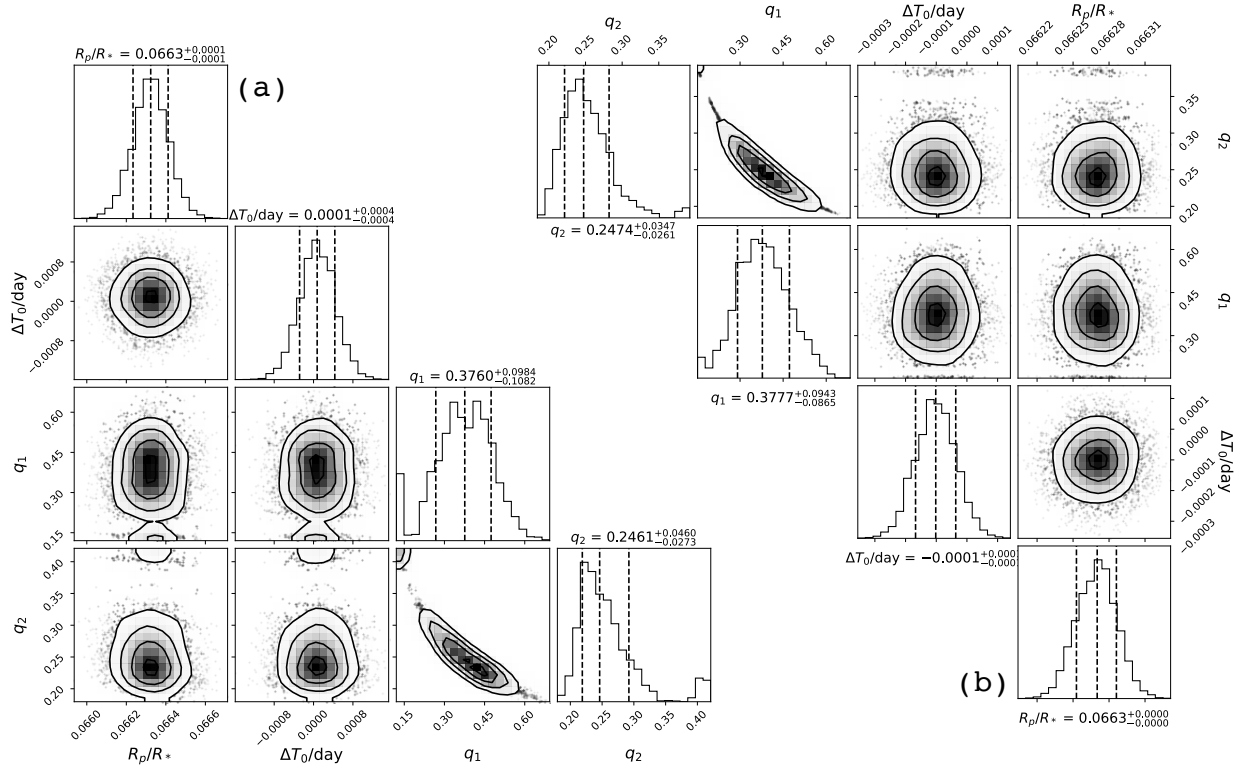


Figure 2.B3: (a) K2 C5 light curve posterior distributions for the planet-only model shown in the top panel of Figure 2.B2. (b) K2 C18 light curve posterior distributions for the planet-only model shown in the middle panel of Figure 2.B2.

Chapter 3

Properties of Potential ExoEarth Host Stars

A previous version of this chapter was published in: Harada, C. K., Dressing, C. D., Kane, S. R., & Ardestani, B. A., 2024, The Astrophysical Journal Supplement Series, 272(2), 30.



The Decadal Survey on Astronomy and Astrophysics 2020 has recommended that NASA realize a large IR/optical/UV space telescope optimized for high-contrast imaging and spectroscopy of ~ 25 exoEarths and transformative general astrophysics. The NASA Exoplanet Exploration Program (ExEP) has subsequently released a list of 164 nearby ($d < 25$ pc) targets deemed the most accessible to survey for potentially habitable exoplanets with the Habitable Worlds Observatory (HWO). We present a catalog of system properties for the 164 ExEP targets, including 1744 abundance measurements for 14 elements from the Hypatia Catalog and 924 photometry measurements spanning from 151.6 nm to 22 μm in the GALEX, Strömgren, Tycho, Gaia, Two Micron All Sky Survey, and Wide-field Infrared Survey Explorer bandpasses. We independently derive stellar properties for these systems by modeling their spectral energy distributions with Bayesian model averaging. Additionally, by consulting the literature, we identify TESS flare rates for 46 stars, optical variability for 78 stars, and X-ray emission for 46 stars in our sample. We discuss our catalog in the context of planet habitability and draw attention to key gaps in our knowledge where precursor science can help to inform HWO mission design trade studies in the near future. Notably, only 33 of the 164 stars in our sample have reliable space-based UV measurements, and only 40 have a mid-IR measurement. We also find that phosphorus, a bioessential element, has only been measured in 11 of these stars, motivating future abundance surveys. Our catalog is publicly available and we advocate for its use in future studies of promising HWO targets.

3.1 Introduction

The Astronomy and Astrophysics 2020 (Astro2020) Decadal Survey has recommended that NASA devise a large (~ 6 m inscribed diameter), ultra-stable, space-based infrared (IR)/optical/ultraviolet telescope capable of high-contrast (10^{-10}) imaging and spectroscopy (National Academies of Sci-

ences, and Medicine, Engineering 2021). Currently named the Habitable Worlds Observatory (HWO) and targeted to launch in the 2040s, the mission’s primary science goals will be to search for biosignatures from roughly 25 habitable zone (HZ) exoplanets, while simultaneously enabling transformative general astrophysics.

The Astro2020 report recognized that the unprecedented nature of HWO’s science objectives and technology requirements will require sophisticated planning and review leading up to the mission design stage. Astro2020 therefore recommended a Great Observatory Mission and Technology Maturation Program (GOMAP) whose aim is to make early significant investments in the comaturation of mission concepts and technologies prior to ultimate recommendation and implementation (National Academies of Sciences, and Medicine, Engineering 2021). The outcomes of the GOMAP phase will inform the final design of HWO.

Following the release of Astro2020, the NASA Exoplanet Exploration Program (ExEP) created a Mission Star List¹ for HWO that included 164 stars “whose [hypothetical] exoEarths would be the most accessible for a systematic imaging survey of HZs with a 6-m class space telescope in terms of angular separation, planet brightness in reflected light, and planet–star brightness ratio” (Mamajek and Stapelfeldt 2024). The ExEP Mission Star List (EMSL) was compiled by analyzing nearby bright stars and adopting inputs from the the mission studies for the Large UV/Optical/IR Surveyor (LUVOIR; The LUVOIR Team 2019) and the Habitable Exoplanet Observatory (HabEx; Gaudi et al. 2020). The broad scope of the list was intended to avoid being overly prescriptive in the required starlight suppression technology or mission requirements (Mamajek and Stapelfeldt 2024).

However, while the EMSL contained key observability metrics that were calculated to constrain the sample (e.g., angular separation, contrast ratio between the planet and host star, excess levels of complicating exozodiacal dust, etc.), it lacked other information that may be crucial for identifying a robust sample of potential exoEarths. For example, the high-energy spectrum of the host star can significantly impact habitability (e.g., Segura et al. 2003; Rugheimer et al. 2015b; Roettenbacher and Kane 2017), but the EMSL does not include UV or X-ray radiation measurements. Host-star composition, which reflects the composition of the protoplanetary disk, is linked to the outcomes of planet formation and hence may give us hints as to which targets are more or less likely to host habitable rocky planets (e.g., Gáspár et al. 2016; Santos et al. 2017; Adibekyan et al. 2021; Cabral et al. 2023). While the EMSL includes the host-star metallicity [Fe/H], it is known that the iron abundance alone does not provide a robust proxy for scaling the abundances of other planet-building elements (e.g., Bitsch and Battistini 2020; Jorge et al. 2022).

Starting with the EMSL targets,² in this work we construct a catalog of properties of promising nearby targets for the HWO exoEarth survey. As a step toward building a more complete understanding of these systems and their likelihood of hosting exoEarths, our catalog contains key properties of these stars that are theorized to be linked to planet habitability. This work, and subsequent precursor science studies, will reduce HWO mission design risk by enabling science and

¹https://exoplanetarchive.ipac.caltech.edu/docs/2645_NASA_ExEP_Target_List_HWO_Documentation_2023.pdf

²We will consider a broader set of stars in future work.

engineering trades that will weigh how key design choices and astrophysical realities may impact the yield of potentially habitable planets characterized by HWO. For example, identifying and characterizing the most promising HWO targets early in mission development will inform critical mission requirements such as the inner working angle (IWA), outer working angle, field of regard, sensitivity, settling time, slew speed, wavelength coverage, and number of filters used for detection and characterization of potentially habitable planets. This work is complementary to the Habitable Worlds Observatory Preliminary Input Catalog (Tuchow et al. 2024), which became public during the revision process of this paper.

The rest of this chapter is organized as follows. In Section 3.2, we describe the information we have compiled in this catalog, which includes the original EMSL data, photometry from six different surveys, 14 elemental abundances, flare rates, stellar variability, and X-ray detections. In Section 3.3, we describe our analysis of stellar properties derived from SED fitting and the verification of stellar abundances from the literature. We discuss our results and implications of our catalog in Section 3.4, and conclude in Section 3.5.

3.2 Data

The ExEP Mission Star List

Motivated by the Astro2020 Decadal Survey, Mamajek and Stapelfeldt (2024) created the EMSL with 164 bright stars whose exoEarths would be the most accessible for a systematic imaging survey of nearby HZs. To allow flexibility in HWO mission design trade studies and the mission target list, they considered different constraints on the observatory’s IWA, exoplanet brightness limits, planet-to-star brightness ratio, the presence of circumstellar debris disks, and stellar multiplicity. Their sample was limited to nearby stars whose HZs would be accessible to a 6 m class telescope with starlight suppression technology (capable of contrast down to 2.5×10^{-11} in the R_c band), and whose HZ terrestrial planets would be bright enough to be imaged and spectroscopically characterized on relatively short timescales (planet magnitudes of $R_c \leq 31$ for integration times up to 60 days; Mamajek and Stapelfeldt 2024). We briefly summarize their results here.

Following the LUVOIR and HabEx mission studies (The LUVOIR Team 2019; Gaudi et al. 2020), the EMSL assumes an occurrence rate of terrestrial HZ planets of $\eta_{\oplus} = 0.24$, thus requiring a sample of at least ~ 100 targets to achieve the Astro2020 goal of imaging at least 25 exoEarths. Their calculations adopted the conservative HZ limits, defined as the range of semimajor axes between 0.95 and 1.67 au for a solar twin for planets between 0.8 and $1.4 R_{\oplus}$ (Kasting et al. 1993; Kopparapu et al. 2013). For other stellar spectral types, the semimajor axis limits are scaled by the square root of the solar-normalized stellar luminosity.

Starting from a large initial sample of nearby AFGKM stars, which was descended from the Extreme Precision Radial Velocity (EPRV) Working Group Final Report³ (Crass et al. 2021), the EMSL was constructed by filling in additional targets from various sources with overlapping spec-

³The EPRV Working Group target list was itself drawn from the LUVOIR and HabEx study reports (The LUVOIR Team 2019; Gaudi et al. 2020).

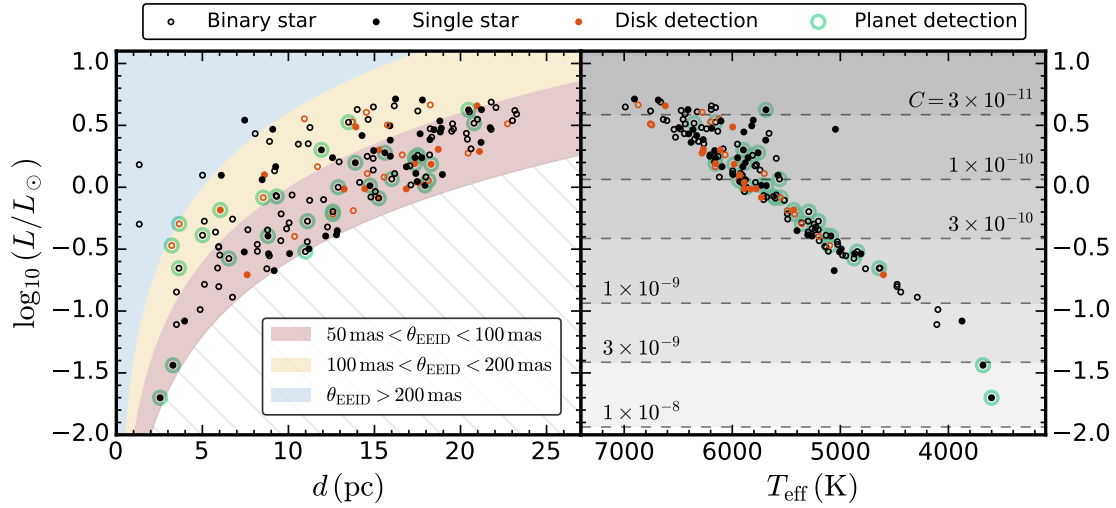


Figure 3.1: Left: EMSL stellar luminosity vs. distance (data from Mamajek and Stapelfeldt 2024). The shaded areas show different ranges of the Earth-equivalent insolation distance (EEID) in angular units. Right: H–R diagram for EMSL stars. The shaded intervals show the expected planet-to-star contrast ratio for a $1 R_{\oplus}$ planet at the EEID, assuming a geometric albedo of $A_g = 0.2$ at a phase angle of $\alpha = 90^\circ$. In both panels, the closed circles show single stars, while the open circles show stars in binary systems with angular separations $> 3''$. The red circles indicate the presence of a circumstellar debris disk, and the green rings highlight systems known to host at least one planet.

tral types, magnitudes, and distances. For this volume-limited sample of approximately 800 stars, Mamajek and Stapelfeldt (2024) calculated the angular separation and expected planet brightness assuming 12 different scenarios with various combinations of orbital distance, phase angle, and planet radius.

In their calculations, Mamajek and Stapelfeldt (2024) adopted Cousins R_c -band photometry because of the R_c filter’s overlapping wavelength coverage with the LUVOIR and HabEx band-passes. Following the LUVOIR and HabEx mission studies, they assumed a planetary geometric albedo of $A_g = 0.2$ for all systems. Then, for each star, they calculated the Earth-equivalent instellation distance (EEID), defined as the orbital separation at which a planet receives the equivalent flux as Earth at 1 au:

$$r_{\text{EEID}} = 1 \text{ au} \sqrt{L_{\star}/L_{\odot}}, \quad (3.1)$$

where $L_{\star}$ is the stellar luminosity⁴.

Assuming a circular orbit and maximum angular separation, this can also be written in terms of the projected angular separation (in milliarcseconds) as

$$\theta_{\text{EEID}} = r_{\text{EEID}}/d_{\text{pc}} = r_{\text{EEID}}\varpi_{\text{mas}}, \quad (3.2)$$

⁴Note that this basic scaling relation does not account for the detailed spectra of nonsolar type stars, which can influence the actual amount of flux received by a planet and hence its temperature.

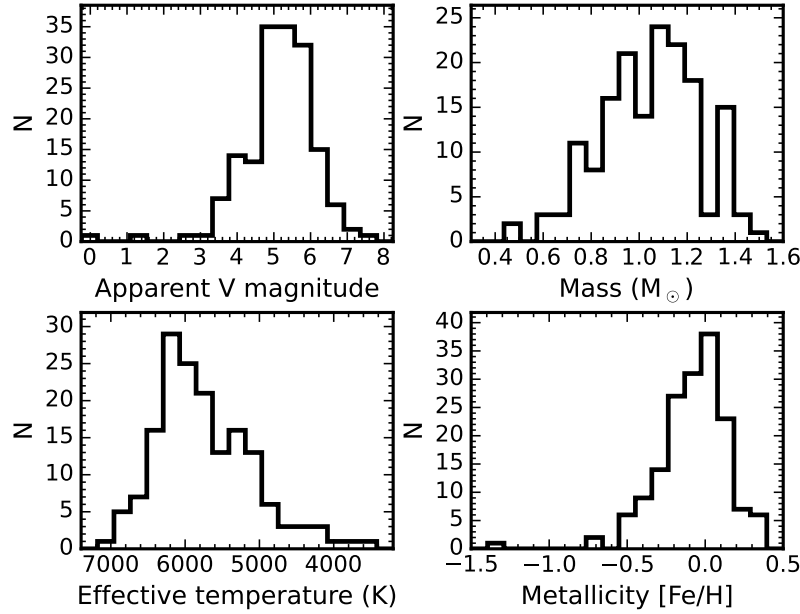


Figure 3.2: Histograms of the apparent V magnitudes, stellar masses, effective temperatures, and metallicities of EMSL stars (data from Mamajek and Stapelfeldt 2024).

where d_{pc} is the distance to the star in parsecs and ϖ_{mas} is the parallax angle in milliarcseconds.

Then, Mamajek and Stapelfeldt (2024) calculated the planet-to-star brightness ratio (contrast) as

$$C = F_p/F_\star = A_g \phi(\alpha) (R_p/r)^2, \quad (3.3)$$

where A_g is the geometric albedo, $\phi(\alpha)$ is the integral phase function at phase angle α (i.e., the observer–planet–star angle), R_p is the planet’s radius, and r is the separation between the planet and its host star. They assumed that all planets had circular orbits (such that r is equivalent to the semimajor axis a) and adopted a simple Lambertian phase function for isotropic scattering:

$$\phi(\alpha) = \frac{1}{\pi} [\sin \alpha + (\pi - \alpha) \cos \alpha]. \quad (3.4)$$

The R_c magnitude of an Earth-size planet was then calculated from the contrast ratio C as

$$R_{c,p} = R_{c,\star} - 2.5 \log_{10} C, \quad (3.5)$$

where $R_{c,\star}$ is the magnitude of the host star.

The initial ~ 800 systems were ranked by the number of test scenarios (out of 12) where the hypothetical planet satisfied predefined limits on angular separation, contrast ratio, and apparent planet R_c magnitude. These limits were informed by the predicted performance of future direct-imaging technology under development for HWO (Mamajek and Stapelfeldt 2024). Further constraints on the presence of debris disks and stellar multiplicity narrowed down the final EMSL list

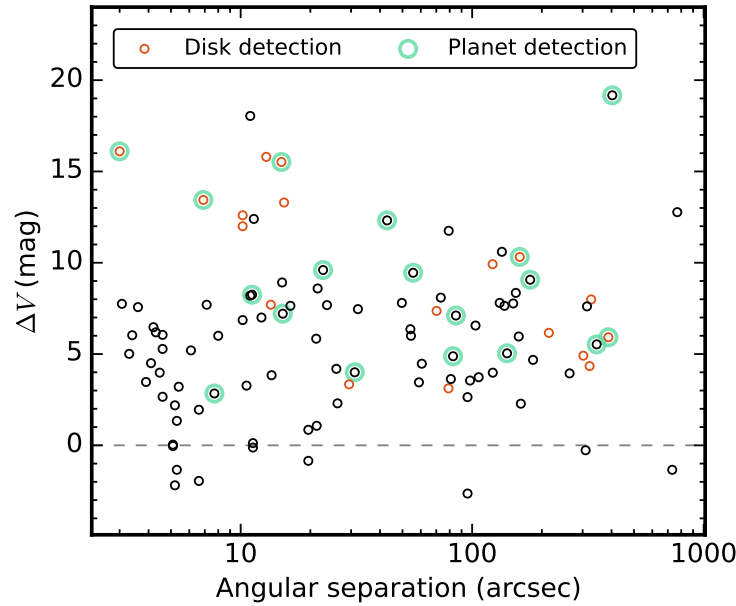


Figure 3.3: Angular separation vs. difference in apparent V magnitude for EMSL binary systems (data from Mamajek and Stapelfeldt 2024). As in Figure 3.1, the red circles show systems with a debris disk, and the green rings indicate systems with at least one known planet.

to 164 targets, which were then assigned to a tier (A, B, or C). The authors considered tier A to be the “best” targets for an HWO exoEarth survey, while tiers B and C contained targets with one or more potential issues which made them less optimal targets than tier A. The final EMSL contains 47 stars in tier A, 61 stars in tier B, and 66 stars in tier C. The criteria defined by Mamajek and Stapelfeldt (2024) for each tier are summarized in Table 3.1. We refer the reader to the original ExEP report for a comprehensive discussion of the target selection criteria.

We accessed the latest version of the EMSL⁵ via the NASA Exoplanet Archive Table Access Protocol. In this work, we include each of the EMSL table columns as they were originally published, with a few minor corrections. We correct any minor inconsistencies identified here and note them in Appendix 3.A (e.g., the EMSL table that we downloaded contained an empty column that we do not use here).

We plot the full sample of EMSL stars in the luminosity–distance plane and in the H–R diagram in Figure 3.1. Figure 3.2 shows histograms of the apparent V magnitude, stellar mass, effective temperature, and metallicity of the EMSL stars. Figure 3.3 highlights the range of angular separations and magnitude differences between binary stars across the sample. All values plotted in Figures 3.1, 3.2, and 3.3 are taken from the original EMSL (Mamajek and Stapelfeldt 2024).

In the following sections, we expand upon the original EMSL by adding columns with addi-

⁵Accessed on 2024 February 7; https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=DI_STARS_EXEP.

Parameter	Tier A	Tier B	Tier C
Number of stars	47	51	66
IWA constraint	83 mas	72 mas	65 mas
Planet brightness limit (R_c)	30.5	31.0	31.0
Planet-to-star contrast limit	4×10^{-11}	4×10^{-11}	2.5×10^{-11}
Disk criterion	No known dust disks of any kind	No disk; Kuiper Belt disk permitted if $L_{\text{disk}}/L_{\star} \leq 10^{-4}$	All disks permitted
Treatment of binaries	Single or binary companion at $> 10''$	Single or binary companion at $5''\text{--}10''$	Single or binary companion at $3''\text{--}5''$

Note. Table reproduced from Mamajek and Stapelfeldt (2024).

Table 3.1: Summary of EMSL Tier Criteria.

tional system properties. A summary of all column names, descriptions, units, and references in our catalog are provided in Table 3.B1 in this chapter’s appendix.

Photometry

For each of the 164 EMSL stars we searched for archival photometry spanning 151.6 nm to 22 μm . In order to accurately crossmatch the sources in the EMSL table with various photometric catalogs, we first crossmatched the EMSL stars with the Transiting Exoplanet Survey Satellite (TESS) Input Catalog⁶ (TIC; Stassun et al. 2019) using the TIC ID provided in the EMSL. From the TIC, we obtained Gaia DR2 IDs, which were then crossmatched to Gaia DR3 IDs using the Gaia DR3 dr2_neighborhood crossmatch table⁷ (European Space Agency (ESA) and DPAC Consortium 2020a; Gaia Collaboration et al. 2023). For sources without a Gaia DR2 ID, we used the HIPPARCOS ID provided in the EMSL to crossmatch the sources with Gaia DR3. We identified Gaia DR3 IDs for all sources except for α Cen A, which is the brightest star in the sample ($V \approx 0$) and too bright for Gaia.

Gaia DR3

Using the crossmatched Gaia DR3 IDs, we obtained Gaia optical photometry and associated uncertainties in the G (330–1050 nm), G_{BP} (330–680 nm), and G_{RP} (630–1050 nm) bandpasses from the Gaia DR3 gaia_source table⁸ (Gaia Collaboration et al. 2016, 2023), which we accessed via VizieR⁹ (Gaia Collaboration 2022a). Due to quality issues that we attribute to detector saturation, we do not include Gaia photometry for α Cen A/B.

⁶Accessed from the Mikulski Archive for Space Telescopes (MAST) via astroquery (Astropy Collaboration et al. 2013, 2018).

⁷https://gaia.aip.de/metadata/gaiaedr3/dr2_neighbourhood/

⁸https://gaia.aip.de/metadata/gaiaedr3/gaia_source/

⁹<https://vizier.cds.unistra.fr/viz-bin/VizieR>

ALLWISE

We obtained mid-IR photometry from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) in four bandpasses: W_1 (3.4 μm), W_2 (4.6 μm), W_3 (12 μm), and W_4 (22 μm). Using the Gaia DR3 `allwise_best_neighbor` table¹⁰ (European Space Agency (ESA) and DPAC Consortium 2021b; Gaia Collaboration et al. 2023), we crossmatched the Gaia DR3 IDs of our target stars to their respective identifiers in the AllWISE Catalog, which we accessed using VizieR (Cutri et al. 2021), and collected the photometry and associated uncertainties for each source where it was available. We do not include any photometry reported to be blended with extended sources, or otherwise flagged as contaminated or poor quality (signal-to-noise ratio < 2). We find measurements satisfying these criteria for 17, 19, 33, and 40 stars in the W_1 , W_2 , W_3 , and W_4 bandpasses, respectively.

2MASS

We followed a similar procedure to acquire near-IR photometry. We used the Two Micron All Sky Survey (2MASS) best neighbor table provided by Gaia DR3¹¹ (European Space Agency (ESA) and DPAC Consortium 2021a; Gaia Collaboration et al. 2023) to crossmatch the Gaia DR3 IDs of our target stars to their respective 2MASS identifiers (Skrutskie et al. 2006). We then used the 2MASS IDs to obtain J (1.24 μm), H (1.66 μm), and K_s (2.16 μm) photometry and associated uncertainties from the 2MASS All-Sky Catalog of Point Sources on VizieR (Cutri et al. 2003). We excluded any data with an extended source contamination flag or artifact contamination and confusion flag. We also removed any bad photometry indicated by a photometric quality flag of “X,” “U,” “F,” or “E.” This resulted in J -band photometry for 130 stars, H -band photometry for 127 stars, and K_s -band photometry for 95 stars.

Tycho-2

In the optical, we added space-based photometry from the Tycho-2 Catalogue of the 2.5 Million Brightest Stars (Høg et al. 2000a), with measurements from the ESA HIPPARCOS satellite’s Star Mapper. We crossmatched the Gaia DR3 IDs of our stars to their Tycho-2 identifiers using the Gaia DR3 `tycho2tdsc_merge_best_neighbor` table¹² (European Space Agency (ESA) and DPAC Consortium 2020b; Gaia Collaboration et al. 2023), then obtained B_T (430 nm) and V_T (530 nm) photometry and associated uncertainties from the Tycho-2 Catalog on VizieR using the crossmatched IDs (Høg et al. 2000b). We found both B_T and V_T photometry for a total of 132 stars in our sample.

¹⁰https://gaia.aip.de/metadata/gaiaedr3/allwise_best_neighbour/

¹¹https://gaia.aip.de/metadata/gaiaedr3/tmass_psc_xsc_best_neighbour/

¹²https://gaia.aip.de/metadata/gaiaedr3/tycho2tdsc_merge_best_neighbour/

Strömgren

We obtained additional ground-based UV/optical photometry from the Strömgren–Crawford *uvby β* Photometry Catalog (Paunzen 2015a) on VizieR (Paunzen 2015b). We crossmatched our sources with the Paunzen (2015a) catalog using the Tycho-2 IDs identified in the previous section. We collected photometry and associated uncertainties in the Strömgren *u* (350 nm), *v* (411 nm), *b* (467 nm), and *y* (547 nm) bandpasses for 130 of our catalog stars.

GALEX

Finally, we obtained UV photometry from the Galaxy Evolution Explorer (GALEX; Martin et al. 2005), which includes two bands at 135–175 nm (far-ultraviolet, FUV) and 175–275 nm (near-ultraviolet, NUV). We used the *astroquery* Xmatch service (Astropy Collaboration et al. 2013, 2018) to crossmatch the Gaia DR3 coordinates of our target stars with any GALEX sources within a 30'' radius in the Revised Catalog of GALEX Ultraviolet Sources (Bianchi et al. 2017). We collected the FUV and NUV magnitudes with their respective uncertainties of the nearest neighbor GALEX source, and excluded any measurements whose associated artifact or extraction flags were nonzero. We report reliable GALEX measurements for 27 stars in the FUV and 12 stars in the NUV.

Stellar Abundances

The Hypatia Catalog is a publicly available spectroscopic abundance catalog consisting of data from 84 literature sources for 50 elements across 3058 stars within 150 pc of the Sun (Hinkel et al. 2014). We obtained stellar abundances for 14 elements from the Hypatia Catalog, including key terrestrial-planet building blocks (e.g., Si, Mg, Al, Fe, and Ni) as well as elements that are essential for life on Earth (e.g., C, N, O, P, and S). All of the retrieved abundances were normalized assuming solar values from Asplund et al. (2009).

We queried the catalog using the Hypatia application programming interface (API),¹³ first attempting to crossmatch sources with the Tycho-2 IDs. If the Tycho-2 ID initially failed to return a match, we iteratively reattempted the query using the 2MASS ID, HD name, common name, and finally the Gaia DR2/DR3 ID. For each successful match, we collected all available abundance measurements for the elements listed in Table 3.2, and recorded the mean, minimum, maximum, and standard deviation of the reported values. In cases where only a single abundance measurement was reported for a given element, we assigned an uncertainty equivalent to the median abundance uncertainty of all the other stars in the sample. For completeness, we also include the total number of abundance values per element for each star in our catalog, in addition to the original literature references for the minimum and maximum abundance values.

A summary of the retrieved abundances is provided in Table 3.2. Histograms of the mean, minimum, and maximum abundance values are shown in Figure 3.4.

¹³Accessed on 2024 February 7; <https://www.hypatiacatalog.com/api>.

Element	No. Stars	No. Measurements	Min. (dex)	Median (dex)	Max. (dex)
[Li/H]	108	361	-2.11	0.97	2.37
[C/H]	141	803	-1.27	-0.02	0.66
[N/H]	96	165	-1.41	-0.04	0.76
[O/H]	140	928	-0.71	0.02	0.38
[Na/H]	150	1200	-1.58	-0.02	0.56
[Mg/H]	148	1143	-1.13	-0.04	0.42
[Al/H]	148	1030	-1.22	-0.04	0.49
[Si/H]	152	1438	-1.10	-0.02	0.43
[P/H]	11	17	-0.28	-0.04	0.54
[S/H]	132	504	-0.46	0.03	1.02
[K/H]	62	88	-0.81	0.20	0.62
[Ca/H]	150	1192	-1.09	-0.03	0.36
[Fe/H]	155	2811	-1.30	-0.05	0.39
[Ni/H]	151	1381	-1.38	-0.06	0.46

Note. Data were retrieved from the Hypatia Catalog (Hinkel et al. 2014).

Table 3.2: Summary of Stellar Abundance Data.

Stellar Flare Rates

We include estimated flare rates for our sample based on light-curve observations from the TESS mission (Ricker et al. 2014). Using data from the first 39 sectors of TESS observations, Pietras et al. (2022) presented a statistical analysis and extensive catalog of stellar flare events identified in the 2 minute cadence light curves of 330,000 stars using the WARPFINDER automated detection pipeline. We used the TIC identifiers of our targets to crossmatch our catalog with the flare events reported in the Pietras et al. (2022) flare catalog.

For each crossmatched source, we recorded the number of flares detected (in the first 39 sectors of TESS observations), in addition to the relative amplitude and estimated total energy released by the most energetic flare. Then, using the Lightkurve package (Lightkurve Collaboration et al. 2018) to access all 2 minute cadence TESS observations of each target on MAST, we determined the number of TESS sectors with observations and how many of these sectors were observed up to sector 39. We note that 148 of our stars have at least one sector of TESS observations, and the median number of TESS sectors observed per star is 3. Using this information, combined with the known duration of each sector (27.4 days; Ricker et al. 2014), we calculated the stellar flare rate (in s^{-1}) for each star with at least one flare detected by Pietras et al. (2022). We identified 44 such stars in our sample.

For completeness, we also checked for flares using the Yang et al. (2023) catalog of stellar flares from TESS. Using data from cycles 1–30 of TESS, Yang et al. (2023) independently measured 60,810 flare events from 13,478 stars. We identified two additional flare sources in the Yang et al. (2023) catalog that were not found in the Pietras et al. (2022) sample of 44 stars: HD 166 and GJ 811. For these two targets, we recorded the number of flares detected in the first 30 sectors of TESS observations and the relative amplitude and energy released by the most energetic flare

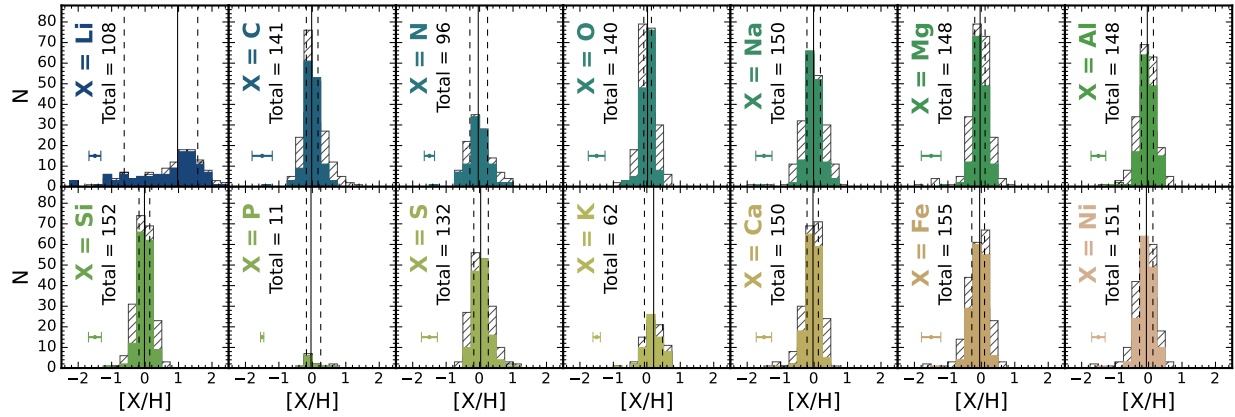


Figure 3.4: Stellar abundance histograms for the 14 elements retrieved from the Hypatia Catalog (Hinkel et al. 2014). For stars with multiple measurements of the same element, the shaded histograms are computed assuming the mean abundance value and the gray-hatched histograms are computed assuming the minimum and maximum abundance values. The element name and corresponding number of stars with at least one abundance measurement for that element are labeled in each panel, and a representative error bar showing the average difference between the minimum and maximum abundance values is shown in the lower-left-hand corner. The vertical lines show the sample median values, and the dashed lines show the 16th and 84th percentiles. Note that the lithium abundances show the greatest amount of spread across the sample due to the strong dependence of $[\text{Li}/\text{H}]$ on stellar age.

(Yang et al. 2023). We also estimated the flare rate following the procedure described above. A histogram of all 46 TESS flare rates and a plot of the flare energy as a function of stellar effective temperature are shown in Figure 3.5.

We also searched the literature for stellar flare information at higher-energy wavelengths. We identified seven systems in our catalog with X-ray flare detections. These X-ray flares were identified in the XMM-Newton serendipitous source catalog (Pye et al. 2015) for 61 Cyg A/B, 70 Oph A/B, ξ Boo A, HD 95735, 3 UMa, ε Eri, and κ 1 Cet. In our catalog, we include an X-ray flare detection flag for these sources. We discuss X-ray emission further at the end of this section.

Stellar Variability

We obtained stellar variability information for our stars using the Variability Catalog of Stars Observed during the TESS Prime Mission (Fetherolf et al. 2023). This catalog contains over 84,000 periodic variables (with periods ranging from 0.01–13 days) identified with high or moderate confidence, including $\sim 65,000$ variable stars that were not previously identified in the literature.

We used the TIC identifiers to crossmatch our targets with the Fetherolf et al. (2023) variability catalog, which we downloaded from MAST. For each crossmatched source, we collected the type of variability solution (i.e., single or double sinusoid or autocorrelation function) in addition to the variability period(s) and amplitude(s). The single-sinusoid periodic signals may indicate a variety

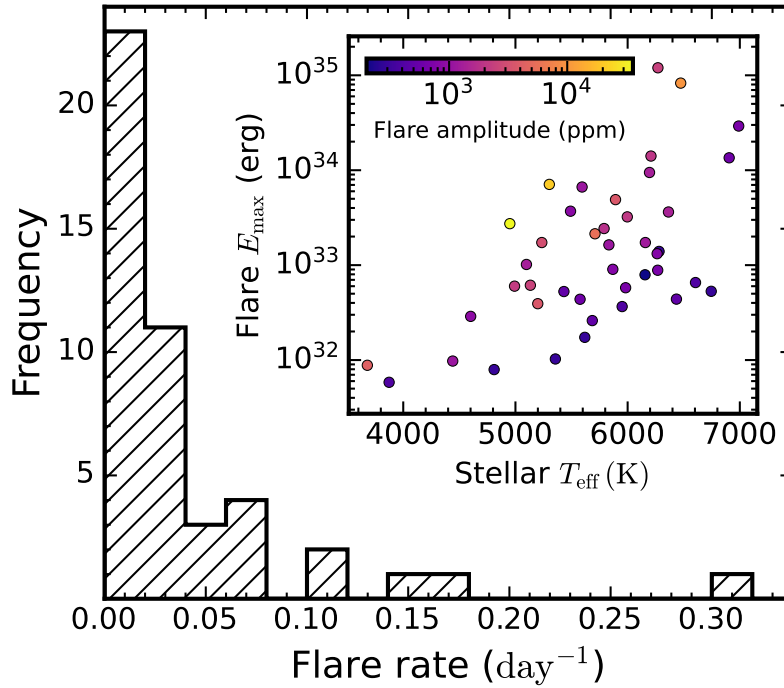


Figure 3.5: Histogram of stellar flare rates from TESS, calculated using the results of Pietras et al. (2022) and Yang et al. (2023). The inset plot shows the estimated energy released by the most energetic flare as a function of stellar effective temperature. The color bar indicates the measured relative flare amplitude.

of stellar activities, including rotational variations caused by starspot activity, a dominant pulsation mode, or ellipsoidal variations in stellar binaries. On the other hand, double-sinusoid solutions are preferred for stars with multiple dominant periodicities, such as multimodal pulsations or differential stellar rotation, while autocorrelation function (ACF) solutions typically represent short-period eclipsing-binary systems or periodic nonsinusoidal rotational variability (Fetherolf et al. 2023).

We found 78 stars in our sample with an indication of variability in TESS observations. Examples of variable TESS light curves with different classifications from Fetherolf et al. (2023) are shown in Figure 3.6. The TESS photometry were downloaded from MAST using the *Lightkurve* package (Lightkurve Collaboration et al. 2018). We plot the luminosity of these stars as a function of their variability periods in Figure 3.7.

For completeness, and to search for variable sources with periods longer than 13 days, we also queried the American Association of Variable Star Observers (AAVSO) International Variable Star Index (VSX). This comprehensive variability catalog combines variable star observations from multiple published sources utilizing both ground- and space-based photometry.¹⁴ We successfully crossmatched 65 stars with the VSX catalog classified as either “variable” or “suspected variable,” of which 30 were not included in the Fetherolf et al. (2023) TESS catalog. For each of these

¹⁴<https://www.aavso.org/vsx/index.php?view=about.top>

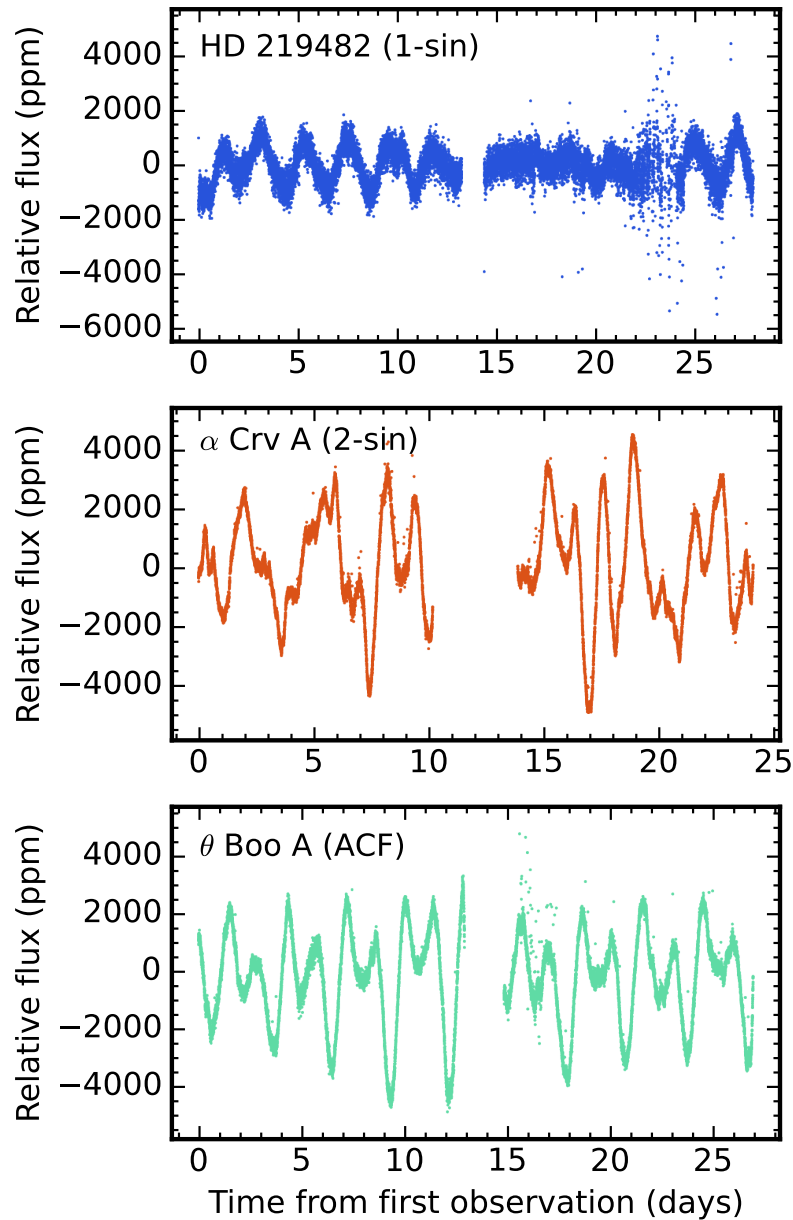


Figure 3.6: Example TESS light curves for variable stars in the EMSL classified by Fetherolf et al. (2023). The top panel shows an example of a single-sinusoid solution for HD 219482, the middle panel shows a double-sinusoid solution for α Crv A, and the bottom panel shows an ACF solution for θ Boo A. The data used to create this figure were downloaded from MAST using the `Lightkurve` package (Lightkurve Collaboration et al. 2018).

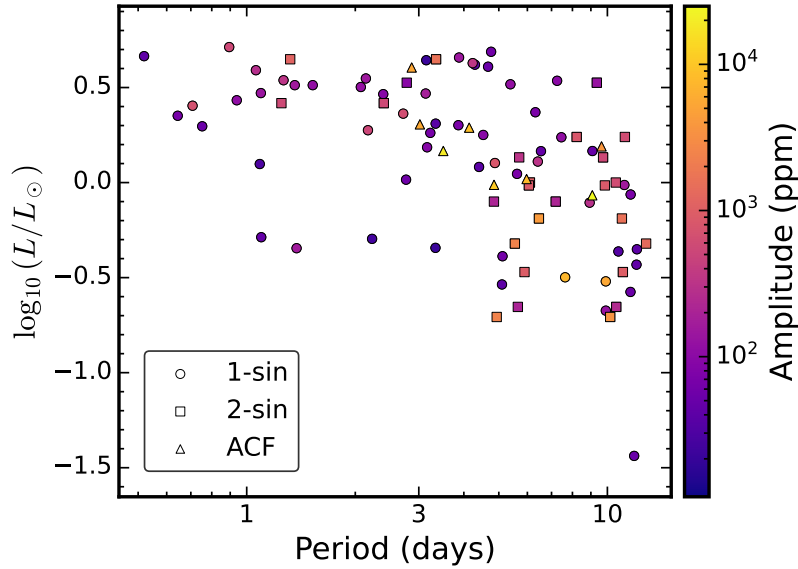


Figure 3.7: Stellar luminosity vs. variability period for variable stars classified in the Fetherolf et al. (2023) catalog. The color bar indicates the relative variability amplitude, and the variability solution type is indicated by the marker shape.

65 stars, we provide a URL link to the respective VSX entry in our catalog.

X-Ray Emission

Lastly, we identified sources in our catalog with previous X-ray detections by crossmatching our sample with the Millions of Optical/Radio/X-ray Associations (MORX) Catalogue (Flesch 2016, 2024). MORX combines published optical, radio, and X-ray sky catalogs to match probable radio/X-ray associations with optical counterparts for over 3,000,000 sources. The catalog includes X-ray detections from the Chandra (Weisskopf et al. 2000), XMM-Newton (Jansen et al. 2001), Swift (Burrows et al. 2005), and ROSAT (Voges et al. 1999) satellite missions.

We used VizieR (Flesch 2024) and the astroquery Xmatch service (Astropy Collaboration et al. 2013, 2018) to crossmatch the Gaia DR3 coordinates of our targets with any sources identified in the MORX catalog within a $30''$ radius. We collected the Chandra, XMM-Newton, Swift, and/or other identifiers of the best neighbor X-ray source. We verified that each crossmatched source was classified as a star and an X-ray source by checking the corresponding quality flags and requiring that the MORX algorithm was $> 80\%$ confident in the classification. We identified 41 of our targets in the MORX catalog, bringing the total number of sources in our catalog with X-ray emission up to 46 (including the X-ray flare detections described earlier in this section).

3.3 Analysis

Stellar SED Fitting

Using the photometry collected from the literature (described in Section 3.2), we constructed spectral energy distributions (SEDs) for each star in our catalog, then used the open-source ARIADNE package (Vines and Jenkins 2022) to fit synthetic SED models to the data to independently constrain stellar radii (R_*), masses (M_*), effective temperatures (T_{eff}), and luminosities (L_*).

The ARIADNE code leverages Bayesian model averaging (BMA; e.g., Fragoso et al. 2018) and nested-sampling techniques (Skilling 2004, 2006) to accurately predict stellar properties from SEDs. The advantage of BMA is that it addresses systematic biases between different stellar atmosphere models by incorporating information from each one to arrive at a solution. Specifically, ARIADNE incorporates the PHOENIX (Husser et al. 2013), BT-Settl and BT-Cond (Allard et al. 2012), BT-NextGen (Hauschildt et al. 1999; Allard et al. 2012), Kurucz (Kurucz 1993), and CK04 (Castelli and Kurucz 2003) stellar atmosphere models, which vary in their treatment of opacities and their assumptions regarding stellar abundances, local thermodynamic equilibrium, and convection/overshooting. ARIADNE first fits each stellar model independently, then computes the weighted average of the posterior samples of each model using the Bayesian evidence as the weight. The best-fit parameters and uncertainties are then estimated from this weighted average posterior (Vines and Jenkins 2022).

While ARIADNE includes a built-in framework to automatically retrieve archival photometry for any given Gaia star, we chose to skip this step and use the photometry we retrieved for our catalog in order to preserve consistent crossmatching and quality tolerances. Moreover, we found that photometry automatically retrieved in certain bandpasses was less suitable for SED fitting due to systematic discrepancies with all of the models. In particular, we found that including the GALEX FUV/NUV and Strömgren u photometry would significantly reduce the quality our fits, resulting in unreliable posterior constraints and often large offsets between the models and data. Therefore, we excluded any GALEX FUV/NUV and Strömgren u photometry from our SED analysis. We also note that the version of ARIADNE used here does not support fitting the mid-IR WISE photometry, so these data were also excluded from the analysis.

We selected priors for each fit based on the stellar parameters included in the EMSL, which are summarized in Table 3.3. To avoid overly restrictive priors due to the small uncertainties associated with many of the EMSL parameters, we placed lower limits on the allowed variances of the normal priors used for the effective temperature, surface gravity, and metallicity. For the variance of the normal distance prior, we used the parallax-angle uncertainty reported in the EMSL to calculate a corresponding distance uncertainty, as this was not reported in the EMSL. Finally, for the stellar radius we assumed a uniform prior ranging between $0.5\times$ and $2\times$ the value of the EMSL stellar radius.

We initially included an extinction term (A_V) in our models, but we found that fitting for A_V could in some cases lead to a systematic overestimate of effective temperature compared to the EMSL values. We attributed this result to the small distances to the stars in our sample ($d < 25$ pc), which likely lead to negligible interstellar extinction for some targets. In these cases, including the

Parameter	Prior
T_{eff} (K)	$\mathcal{N}(T_{\text{eff,EMSL}}, \max(\sigma_{T_{\text{eff,EMSL}}}, 100 \text{ K}))$
$\log g$ (cgs)	$\mathcal{N}(\log(g)_{\text{EMSL}}, \max(\sigma_{\log(g)_{\text{EMSL}}}, 0.1))$
[Fe/H]	$\mathcal{N}([\text{Fe/H}]_{\text{EMSL}}, \max(\sigma_{[\text{Fe/H}]_{\text{EMSL}}}, 0.05))$
d (pc)	$\mathcal{N}(1''/\varpi_{\text{EMSL}}, \sigma_{\varpi_{\text{EMSL}}}/\varpi_{\text{EMSL}}^2)$
R_* ($R_{\odot}$)	$\mathcal{U}(0.5R_{*,\text{EMSL}}, 2R_{*,\text{EMSL}})$
A_V (mag) [†]	$\mathcal{U}(0, A_{V,\text{max}})$

Note. $\mathcal{N}(\mu, \sigma)$ represents a normal distribution with mean μ and variance σ^2 ; $\mathcal{U}(a, b)$ represents a uniform distribution bounded between a and b .

[†] Only used for fits where A_V was a free parameter. $A_{V,\text{max}}$ is the maximum line-of-sight extinction from the updated SFD Galactic dust map (Schlegel et al. 1998; Schlafly and Finkbeiner 2011).

Table 3.3: Priors Used for SED Fitting.

A_V parameter could be superfluous and lead to overfitting, resulting in the systematic disagreement in T_{eff} . To mitigate this issue, we ran two different versions of our SED fits: one with an extinction term and one without.

For both cases, we used the BMA algorithm implemented in ARIADNE (Vines and Jenkins 2022) with dynesty nested sampling (Speagle 2020) to derive best-fit parameters and posterior distributions for each of our 164 stars. We found that using 1000 live points and a stopping criterion of $d \log z = 0.5$ resulted in robust, converged posteriors. We then compared the Bayesian evidences of the SED models with and without interstellar extinction and selected the best-fit parameters from the model with the higher Bayesian evidence.

An example of the best-fit SED for the star HD 10476 is shown in Figure 3.8. Note that ARIADNE automatically plots the model from whichever library (i.e., PHOENIX, BT-Settl, BT-Cond, BT-NextGen, Kurucz, or CK04) yielded the highest Bayesian evidence, but the best-fit parameters for the plotted model are estimated from the weighted average posteriors from all of the models. The corresponding BMA posterior distributions for each of the fit parameters are shown in Figure 3.B1 this chapter’s appendix.

Lastly, we note that ARIADNE also estimates stellar age using the SED fit parameters together with the *isochrones* package (Morton 2015a) and the MESA Isochrones and Stellar Tracks library (Dotter 2016). While we caution that single-star isochrone fitting may be insufficient to reliably estimate stellar ages (as is apparent in the wide age uncertainties resulting from many of the ARIADNE fits), we include the estimated ages and uncertainties in our catalog as a baseline for future work investigating stellar ages more closely.

In general, we found that our SED analyses resulted in stellar parameters that were consistent with the EMSL, which itself adopted values from various literature sources (Mamajek and Stapelfeldt 2024). Figure 3.9 shows a comparison between the T_{eff} and R_* derived from our SED fits and those reported in the EMSL. We found that the SED-derived effective temperatures are all consistent with the EMSL values within 3σ , with a residual rms of 41.8 K. For the stellar radii, we

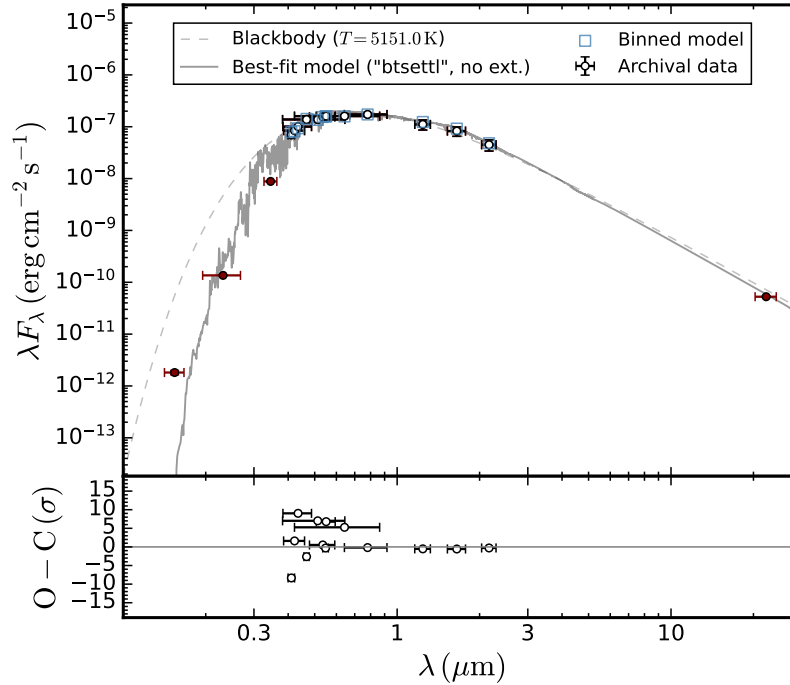


Figure 3.8: Top: Example best-fit SED model for HD 10476 computed with ARIADNE. The points with error bars show the archival photometry, and the blue squares show the synthetic model photometry. The UV and mid-IR points (shown in maroon) were not used to compute the fit. In this case, the overplotted model with the highest Bayesian evidence was the “btsettl” stellar atmosphere with no extinction (Allard et al. 2012). The parameter posterior distributions derived from this example fit are shown in Appendix 3.B. Bottom: Observed minus calculated photometry residuals normalized to the uncertainty the data. *(The full set of 164 SED plots can be accessed online in Harada et al. (2024) at the publisher’s website.)*

found that 94% of the SED-derived values were consistent with the EMSL within 3σ , achieving a residual rms of $0.035 R_{\odot}$. Further discussion of these results is presented in Section 3.4.

Stellar Metallicity Verification

While the original EMSL included stellar metallicity measurements for each star, the assumed values were selected from disparate literature sources (Mamajek and Stapelfeldt 2024). This introduced the possibility of systematic biases that depend on the particular method used to determine the stellar metallicity by each separate source catalog. The Hypatia Catalog (Hinkel et al. 2014) allows for more robust stellar metallicity estimates because it combines multiple values from different source catalogs. These can subsequently be averaged together to yield more statically robust metallicity estimates.

We checked for consistency between the $[\text{Fe}/\text{H}]$ metallicities reported in the EMSL and the average iron abundances from the Hypatia Catalog. The values of $[\text{Fe}/\text{H}]$ from the EMSL and

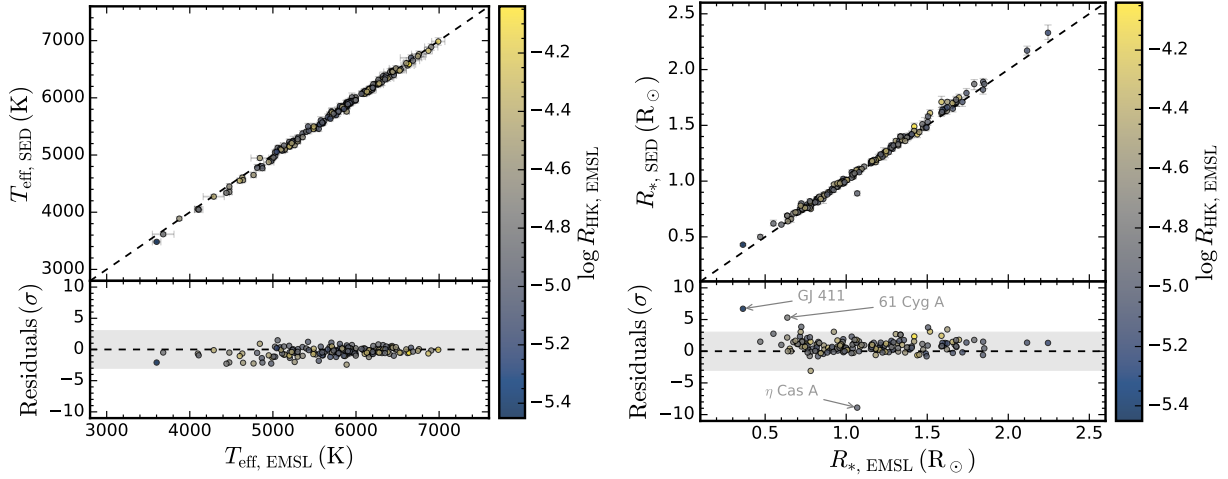


Figure 3.9: Left: Stellar effective temperature (T_{eff}) derived from the ARIADNE SED fits vs. T_{eff} reported in the EMSL table (top), along with the residuals normalized by the quadrature sum of their respective uncertainties (bottom). The black dashed line in the top panel shows a one-to-one correspondence, and the gray shaded box in the bottom panel highlights the region of $< 3\sigma$ discrepancy. Right: same as the left-hand side, but for stellar radius (R_*).

Hypatia are plotted against one another in Figure 3.10. We calculated the discrepancy between the EMSL and Hypatia metallicities (in σ) by taking the quadrature sum of the EMSL metallicity uncertainty and the standard deviation of all Hypatia metallicities. All but one of the stars (GJ 380; see Section 3.4 for discussion) had metallicities from the EMSL and Hypatia that were consistent within 2σ . We calculated the rms of the residuals to be 0.048 dex.

We also note that the metallicity uncertainties we derived from Hypatia are generally larger than those reported in the EMSL (0.065 dex median for Hypatia compared to 0.02 dex median for the EMSL) due to the systematic differences between the various Hypatia source catalogs (e.g., in stellar models, line lists, instrument resolution, instrument wavelength coverage, etc.). In principle, our more conservative metallicity uncertainties are more reliable because they take into account multiple independent analyzes. However, we caution that this means that Figure 3.10 is not necessarily an apples-to-apples comparison, and that real trends could be blurred out due to nonastrophysical effects. We discuss these results further in the next section.

3.4 Discussion

Our updated catalog of properties of 164 promising targets for HWO includes 924 photometry measurements in 18 different bandpasses spanning from 151.6 nm to 22 μm , 1744 abundance measurements for 14 different elements, variability metrics for 78 stars, X-ray detections for 46 stars, and flare rates for 46 stars. A more granular summary of the catalog properties is presented in Figure 3.11, and key physical and observable properties of the stars in our catalog are plotted

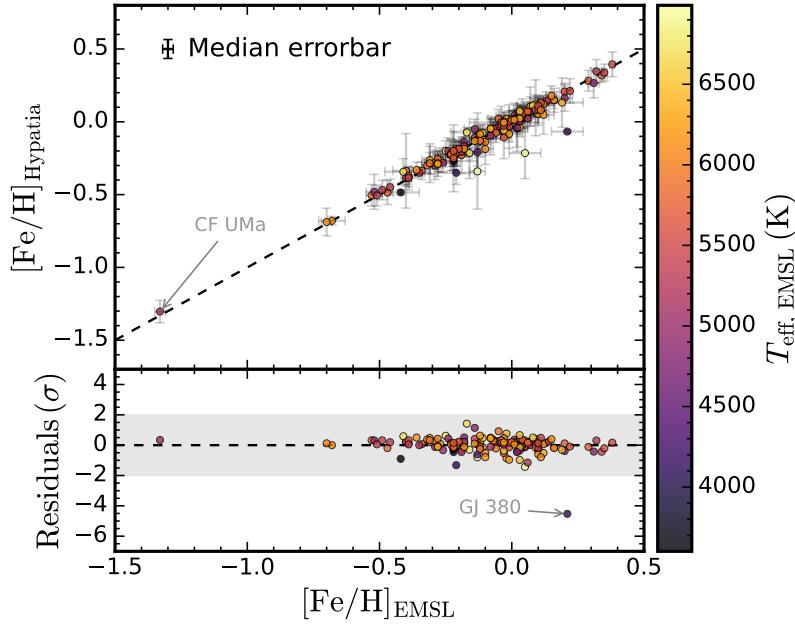


Figure 3.10: Top: Median iron abundance metallicity $[\text{Fe}/\text{H}]$ from the Hypatia Catalog vs. the $[\text{Fe}/\text{H}]$ reported in the original EMSL table. A one-to-one correspondence is shown by the black dashed line. The stellar effective temperature from original EMSL table is indicated by the color bar. A representative 1σ median error bar is shown in the upper left-hand corner. Bottom: The residuals between the median Hypatia and EMSL metallicities, normalized by the quadrature sum of their respective uncertainties. For the Hypatia uncertainties, we used the standard deviation of all listed values. The gray shaded box highlights the region of 2σ consistency.

in Figure 3.B2 in this chapter’s appendix. This catalog of stellar properties is intended to provide a starting point for future precursor and preparatory science leading up to HWO’s final mission design and eventual launch in the 2040s.

Photometry and SED Fits

We produced SEDs for each of the 164 stars in our sample using photometry drawn from the literature, and fit SED models to independently verify stellar parameters. Using Bayesian model averaging and six standard libraries of stellar atmosphere models (Section 3.3), we derived T_{eff} , $R_{\star}$, $M_{\star}$, and $L_{\star}$ that were consistent with the literature values reported in the EMSL. A comparison of our SED fit results and literature values for T_{eff} and $R_{\star}$ are shown in Figure 3.9.

We note that the stellar radius we derived for 10 of our stars appear to be discrepant from the values reported in the literature by more than 3σ : GJ 411, 61 Cyg A, and η Cas A have the largest disagreements. However, close inspection of the SED fits and posterior distributions did not reveal any fits with unexpectedly poor quality. These discrepancies may simply arise due to the lack of radius uncertainties reported in the EMSL, possibly because the stellar radius is often a

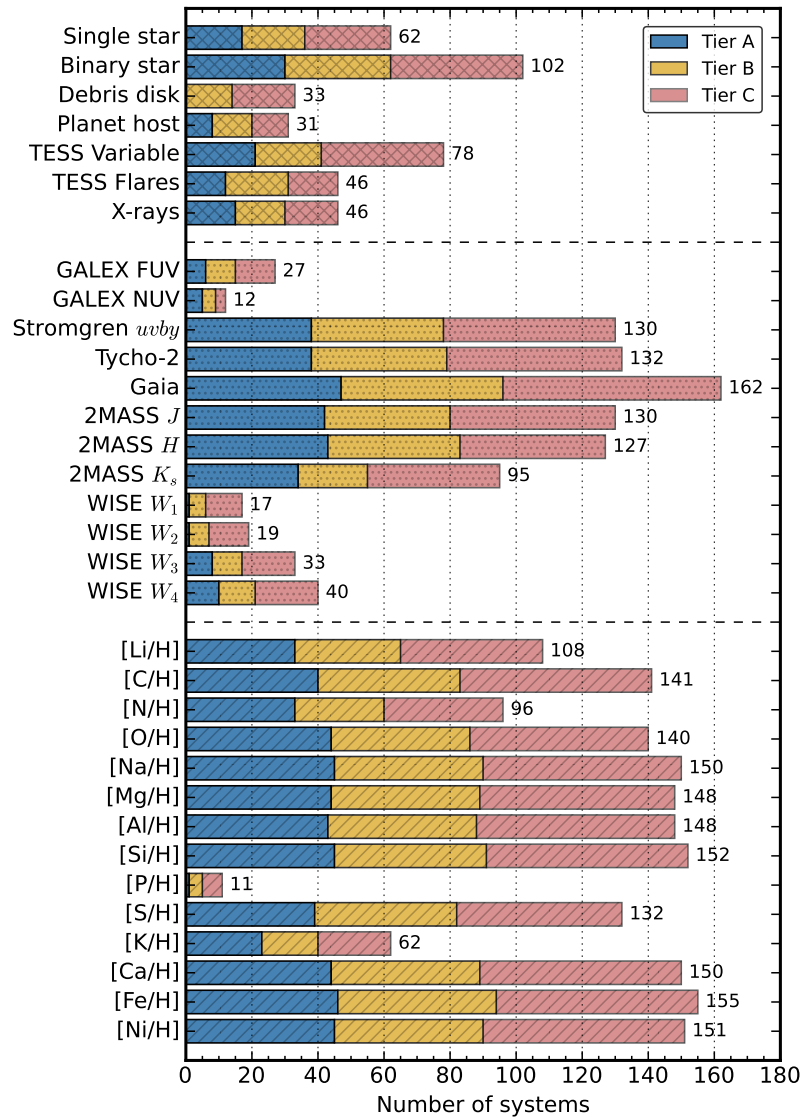


Figure 3.11: Bar graph showing a summary of the information in our catalog, demonstrating the (in)completeness of our knowledge about these systems. Each attribute is subdivided into the three tier levels defined by Mamajek and Stapelfeldt (2024).

calculated, rather than observed, quantity. We also note that the EMSL also does not report stellar mass uncertainties. Knowing the uncertainties associated with both values would be necessary to determine whether these parameters are in fact significantly discrepant in a meaningful way.

Furthermore, we note that the T_{eff} uncertainties from the literature may be underestimated in many cases (e.g., Tayar et al. 2022). The median uncertainty in T_{eff} reported in the EMSL is only 20 K, which is more than a factor of 2 smaller than the median uncertainty we derived from SED fitting (47 K). Our stellar luminosity uncertainties are also about a factor of 2 larger than the literature values. For these reasons, we suggest that future studies of these stars adopt the more conservative stellar parameters from our uniform SED fits.

Stellar SEDs and Planetary Habitability

Planetary habitability is critically linked to the energy output of the host star (Buccino et al. 2007). The EMSL was compiled assuming the classical HZ limits for complete water loss and maximum greenhouse effect (e.g., Kasting et al. 1993; Kopparapu et al. 2013; Kane et al. 2016; Hill et al. 2023), which were scaled by the square root of the stellar luminosity for each star. While this is a useful first approximation, the sensitivity of exoplanet habitability to the SED of the host star is more complex, especially for nonsolar type stars which have fundamentally different SEDs.

Notably, UV radiation from the host star significantly influences the photochemistry of planetary atmospheres, which in turn affects surface UV environments that are connected to the origin and evolution of life (Segura et al. 2003; Buccino et al. 2007). Depending on the incident UV flux, terrestrial planets orbiting different types of stars are also expected to show different atmospheric features that indicate habitability on Earth, such as H_2O , CH_4 , O_3 , and N_2O (Segura et al. 2003; Kaltenegger et al. 2007; Rugheimer et al. 2015a). The effects of UV flux on surface and atmospheric conditions also change throughout geological time as chemical evolution modifies concentrations of O_3 , CH_4 , and hazes in the atmosphere (Rugheimer et al. 2015b).

On the other hand, the mid-IR portion of host-star SEDs may have observational consequences for high-contrast direct imaging of habitable worlds. Significant mid-IR excess, for example, may indicate the presence of exozodiacal dust or warm debris disks (e.g., Trilling et al. 2008), which would degrade the quality of direct imaging and spectroscopy of HZ planets. Mamajek and Stapelfeldt (2024) have indicated in the EMSL which systems have previous detections of circumstellar debris disks, ranking stars with no known dust disks of any kind in tier A, stars with cold Kuiper Belt disks that were very optically thin ($L_{\text{IR}}/L_{\star} < 10^{-4}$) in tier B, and stars with any other type of disk in tier C. For completeness, we have added IR fluxes to our catalog where available, which we hope will assist in future analyses of circumstellar debris disks for this sample.

We note that currently only 33 of the stars in our sample have at least one robust space-based UV measurement, and 40 have at least one mid-IR measurement (assuming the quality cuts described in Section 3.2). These targets account for just 20%–24% of the catalog. While UV observations of potential HWO targets are being worked on by the NASA Astrophysics Decadal Survey Precursor Science (ADSPS) Program, further work is needed to study the radiation environments of stars in our catalog more closely, particularly for stars currently lacking reliable mid-IR and UV measurements.

Stellar Composition

While the EMSL catalog compiled stellar iron abundances from various sources, we have expanded this to include the averaged abundances for 14 elements from the Hypatia Catalog (Hinkel et al. 2014) to facilitate future detailed modeling of planet formation for promising HWO targets. Our catalog includes the primary building blocks of terrestrial planets (e.g., Si, Mg, Al, Fe, and Ni) and the essential ingredients for life on Earth (e.g., C, N, O, P, and S). We identified 155 ($> 94\%$) of our stars with at least one Fe measurement in the Hypatia Catalog, and found measurements of Na, Mg, Al, Si, Ca, and Ni for at least 90% our sample. The abundances are summarized in Table 3.2 and Figure 3.4.

Host-star composition is directly linked to the protoplanetary disk, which in turn controls the formation and subsequent composition of planetary building blocks (Gáspár et al. 2016; Santos et al. 2017; Adibekyan et al. 2021; Cabral et al. 2023). It is therefore commonly assumed that exoplanet composition mirrors that of the host star, although this is not always the case (e.g., Plotnykov and Valencia 2020; Schulze et al. 2021). While the iron abundance $[\text{Fe}/\text{H}]$ is usually known for nearby stars and often used as a proxy for scaling other stellar abundances, this information alone is insufficient for detailed interior modeling of terrestrial planets because planetary building blocks like Si, Mg, and O are understood not to scale linearly with Fe (e.g., Bitsch and Battistini 2020; Jorge et al. 2022). Figure 3.12 demonstrates the known nonlinearity of the correlation between $[\text{Fe}/\text{H}]$ and Si, Mg, C, and O abundances in our sample.

Recent studies have implemented devolatilization models, using the detailed compositions of host stars to infer the composition and internal structure of terrestrial planets and thus demonstrating a range of plausible exoEarth geologies (Hinkel and Unterborn 2018; Wang et al. 2022; Unterborn et al. 2023). For example, solid planet-building blocks formed exterior to the water-ice line depend strongly on the C/O ratio, with a higher C/O in solids leading to smaller water-ice fractions as more O is partitioned in gaseous CO and CO₂ (Bitsch and Battistini 2020).

The Mg/Si ratio is also important to the mineralogy of planet-building blocks. According to geochemical models, planets with low Mg/Si ratios tend to cool more slowly after formation because of high mantle viscosity, leading to rapid loss of volatiles (Spaargaren et al. 2020). Additionally, changing Mg/Si ratios shift the condensation sequence of solid planet-building materials, with lower Mg/Si ratios leading to mechanically stronger mantles and higher Mg/Si leading to weaker mantles (Jorge et al. 2022; Spaargaren et al. 2023). This can carry important consequences for lithosphere dynamics (e.g., plate tectonics, volcanism), which can drive different evolutionary pathways affecting habitability. The C/O ratio of our sample ranges from 0.16 to 1.91 and the Mg/Si ratio ranges from 0.68 to 1.94 (compared to solar values $\text{C}/\text{O}_{\odot} = 0.59$ and $\text{Mg}/\text{Si}_{\odot} = 1.10$; Asplund et al. 2021). Both C/O and Mg/Si as a function of stellar metallicity are shown in Figure 3.13.

Moreover, the composition of the protoplanetary disk (and thus the host star) plays a role in determining the resulting system architectures of planet formation (e.g., Adibekyan et al. 2021). For example, early spectroscopy studies of exoplanet hosts demonstrated that there is a rise in the fraction of stars with planets above solar metallicity (Fischer and Valenti 2005). More recently, Tautvaišienė et al. (2022) analyzed 25 bright planet hosts from TESS and showed that stars with

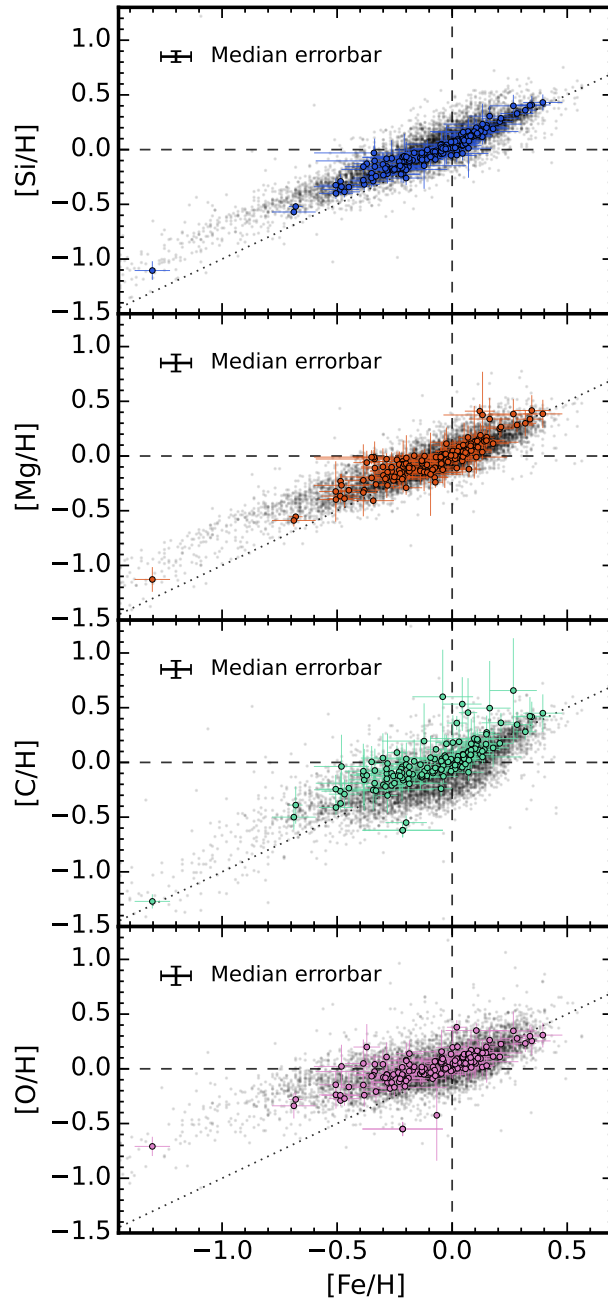


Figure 3.12: Abundances of silicon, magnesium, carbon, and oxygen vs. iron from the Hypatia Catalog (Hinkel et al. 2014). Stars from the catalog presented in this work are shown in color. For reference, all stars with abundance measurements in the Hypatia Catalog are plotted as small gray points. The vertical and horizontal dashed gray lines show solar values, and the dotted line shows a one-to-one correspondence. A representative median error bar is shown in the upper left-hand corner of each panel.

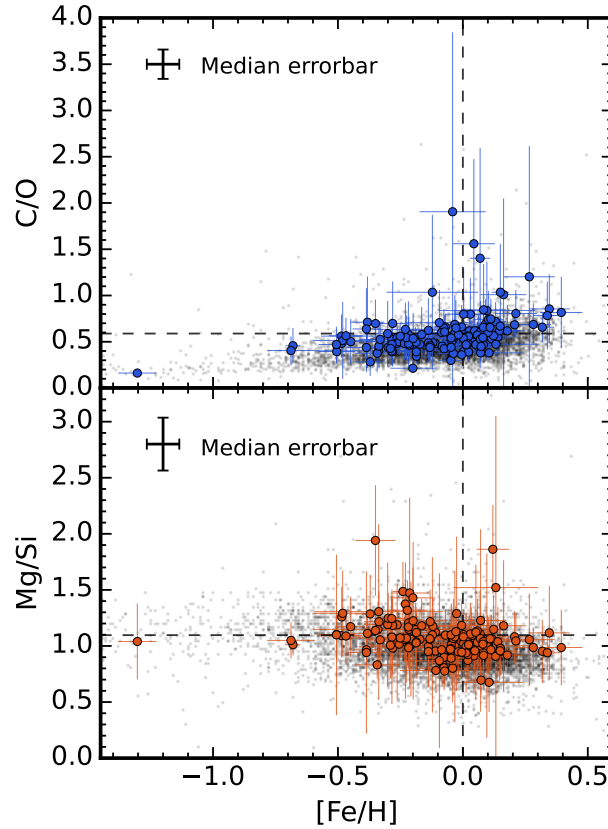


Figure 3.13: C/O (top) and Si/Mg (bottom) ratios vs. stellar metallicity $[Fe/H]$ from the Hypatia Catalog (Hinkel et al. 2014). EMSL stars are shown in color, and all stars with abundance measurements in the Hypatia Catalog are plotted as small gray points for reference. Solar metallicity and abundance ratios ($C/O_{\odot} = 0.59$, $Mg/Si_{\odot} = 1.10$; Asplund et al. 2021) are indicated by the vertical and horizontal dashed gray lines. A representative median error bar is shown in the upper left-hand corner of each panel.

high-mass planets tend to be more metal rich than stars with low-mass planets. The HZ is thought to depend on planetary mass, with larger planets having wider HZs due to their smaller H_2O atmospheric column depths (Kopparapu et al. 2014). Therefore, if metal-rich stars tend to have more massive terrestrial planets, then their HZs may extend further out. This may be an important factor to consider in expanding the list of potential HWO targets.

Another consideration linked to planetary composition is the prevalence of multiplanet systems around stars of different metallicities. Compact multiplanet systems occur more frequently around stars of increasingly lower metallicities, and these systems are nearly mutually exclusive with systems containing hot Jupiters (e.g., Brewer et al. 2018). These system architectures may complicate the dynamical stability of otherwise plausible exoEarths, possibly excluding stable HZ orbits altogether for some systems. The star Groombridge 1830 (CF UMa), which stands out in our catalog with an extremely low metallicity of $[Fe/H] = -1.3$ (labeled in Figure 3.10), may therefore be a

particularly interesting target. Groombridge 1830 is an early K dwarf star with no known planetary companions and a predicted EEID angular separation of about 50 mas.

The abundance of bioessential elements present in the protoplanetary disk may also influence planetary habitability. The element phosphorus, for example, is necessary for all life on Earth because it forms the backbone of DNA and RNA molecules, which encode genetic information and instructions for cell reproduction. Phosphorus is also the limiting biochemical ingredient in adenosine triphosphate (ATP), which is the primary energy source for cellular functions. However, if terrestrial planets form in disks with substantially low P abundances, strong partitioning of P into the cores could rule out sufficient bioavailable P on the surface (Hinkel et al. 2020). Only 11 stars in our catalog ($\sim 7\%$) have measured P abundances, commensurate with the broader dearth of stars with P measurements in the literature. Measuring phosphorus abundances is challenging because the spectral absorption features are faint and fall outside of the optical band typically used for abundance spectroscopy (Hinkel et al. 2020). This motivates future investigations dedicated to measuring P abundances of promising HWO targets.

We note as a caution to the reader that some abundances we collected from the Hypatia Catalog are highly uncertain, with large differences between different source catalogs. We found that 12 stars in our catalog have an [Fe/H] spread greater than 0.5 dex, while two stars, HD 38858 and δ Eri (HD 22049), have an [Fe/H] spread greater than 1.0 dex. In other cases, the metallicity reported in the EMSL disagrees significantly with the average Hypatia [Fe/H] abundance. In the most discrepant case for the star GJ 380 (HD 88230; labeled in Figure 3.10), the EMSL [Fe/H] value was 0.21 ± 0.06 (Soubiran et al. 2022), while the mean Hypatia [Fe/H] value was -0.067 (Hinkel et al. 2014). We ruled out bad crossmatching as an explanation for this discrepancy, and we verified that the range of Hypatia [Fe/H] values spans from -0.08 (Woolf and Wallerstein 2005) to -0.05 Maas et al. (2016). This suggests a possible typographical or crossmatching error with the Soubiran et al. (2022) catalog implemented in the original EMSL for this particular star.

In our catalog, we include the minimum and maximum Hypatia abundance values along with their literature sources. We encourage future studies using our catalog to exercise caution by checking the span of abundance measurements before assuming a particular value.

Stellar Environments

We have identified 108 stars in our sample that exhibit variability, flares, and/or X-ray emission. Furthermore, the EMSL contains over 100 stars in binary systems and four post-main-sequence stars ($\log(g) < 4$). The stars are mostly intermediate in mass, with 66 F-type, 55 G-type, 40 K-type, and only three M-type stars. While this is by no means an exhaustive list of factors that may affect habitability, it provides a useful starting point for discussing how past, present, and future stellar environments are intertwined with planetary surface conditions necessary for life.

Periodic stellar variability is often an indication of radial pulsations (typically in evolved massive stars) or rotationally modulated brightness differences caused by photospheric heterogeneities (typically in cooler dwarf stars). In the latter case, analysis of the photometric time series can yield constraints on the rotation period and starspot coverage of the stellar photosphere. Stellar rotation has been theoretically shown to affect the limits of the HZ, especially in rapidly rotating

A and F stars where the rotational forces cause the star to become oblate and develop a pole-to-equator temperature gradient (Ahlers et al. 2022). Starspot coverage on the other hand is linked to magnetic fields, and hence stellar activity, which has been extensively studied in the context of M-dwarf planet habitability (e.g., Joshi et al. 1997; Scalo et al. 2007; Gallet et al. 2017; Günther et al. 2020). Stellar flares, which are associated with high stellar activity, are high-energy transients that can emit large quantities of UV and X-ray radiation, especially in M and K dwarf stars. Flares present challenges to potential habitability because they can alter the atmospheric chemistry of terrestrial planets (primarily generating O_3 and N_2O) and expose their surfaces to high levels of ionizing radiation (e.g., Ridgway et al. 2023).

Stellar age can also present challenges to potential habitability. While the majority of stars in our sample are main-sequence stars, there are a handful of subgiant stars. Notably, δ Eri (GJ 150) has the lowest surface gravity with $\log(g) = 3.78$. The HZs of post-main-sequence stars move outward as the stellar luminosity increases, which can make them more accessible to direct-imaging surveys. However, stellar mass loss during the red giant branch and asymptotic giant branch phases of post-main-sequence evolution can destabilize planetary orbits and drive strong stellar winds that act to erode planetary atmospheres, possibly reducing the chances of habitability (e.g., Ramirez and Kaltenegger 2016). More detailed modeling is needed to assess the importance of these effects for the few subgiant stars in our catalog. We also leave it to future work to determine more precise stellar ages for this sample.

Ultimately, a holistic assessment of each system will be necessary to select the most promising targets for HWO, informed by both observability (limited by technology) and likely scientific return (limited by precursor knowledge). Therefore, we do not attempt to narrow down the list of potential targets in this work, but rather present what is known about each system at face value in hopes that this information will be used holistically in future studies.

Data Availability

Our catalog of 164 stars is publicly available to the community via the authors' website¹⁵ and the machine-readable version of Table 3.B1. A list of columns included in the published version of the catalog and their descriptions are provided in Table 3.B1 in the appendix of this chapter. We invite the HWO community to use this catalog as a resource for additional investigations into these promising target stars.

Finally, we intend to update this catalog with additional stars and properties at a future time. Expanding the sample of potential HWO targets will enable a more comprehensive investigation in mission design trade space, as a significant portion of EMSL targets may ultimately be determined to be unsuitable for the HWO planet survey (e.g., see Tuchow et al. 2024).

¹⁵<https://calebharada.github.io/spores/>

3.5 Conclusion

We have created a catalog of system properties for 164 stars that are promising targets for the Habitable Worlds Observatory, a future ~ 6 m class space mission capable of high-contrast direct imaging and spectroscopy (National Academies of Sciences, and Medicine, Engineering 2021). Our catalog derives from the NASA Exoplanet Exploration Program’s Mission Star List for HWO, which selected 164 nearby stars whose hypothetical exoEarths would be most accessible to a high-contrast direct-imaging survey in terms of angular separation and planet–star contrast ratio (Mamajek and Stapelfeldt 2024). We include over 1700 individual stellar abundance measurements for 14 elements, over 900 photometry measurements spanning from 151.6 nm to 22 μ m, flare rate estimates for 46 stars, variability metrics for 78 stars, and X-ray detections for 46 stars.

Bayesian analysis of the stellar SEDs yielded broadly consistent stellar parameters compared to previously published values reported in the EMSL. Iron abundances averaged from the Hypatia Catalog (Hinkel et al. 2014) are also mostly consistent with those drawn from the EMSL, but often with much more conservative uncertainties due to significant differences between the various Hypatia source catalogs. The SEDs and different compositions of the potential host stars likely have important consequences affecting their HZs and potential habitable planets, which we have discussed in detail.

We emphasize that the catalog and discussion presented here is intended to aid future work investigating these systems more closely. This work is the first in a series of forthcoming precursor science papers that will result from the NASA ADSPS program.¹⁶ Subsequent precursor science work is critical to HWO trade studies that will determine the final mission design. Throughout this work, we have hinted at future avenues toward science with HWO, including closer investigations of the stars’ high-energy and mid-IR radiation environments, more complete surveys of bioessential element abundances, and studies of dynamical stability in systems with previously detected planets or a higher likelihood of being a compact multiplanet system.

Additionally, future work should investigate the depth of past searches for planets in these systems using archival photometry and public RV observations¹⁷ (Howard and Fulton 2016; Laliotis et al. 2023). A follow-up investigation of stellar variability and rotation rates would also be useful for accurately measuring stellar ages with gyrochronology, and as a proxy for stellar activity. Lastly, as future studies begin to winnow down the list of possible HWO targets, additional stars should also be added to the list to allow for more flexibility in mission design trades. Investing in this work early on in the mission development will reduce costs while maximizing the likelihood of reaching HWO’s goal of detecting life or placing meaningful constraints on the rarity of life on other planets. The EMSL sample studied here was compiled using a somewhat limited definition of the HZ and the assumption of only circular orbits, but this can be expanded by extending the permissible conditions for habitability and adding planets with eccentric orbits. These future pathways toward planet properties were discussed in our ADSPS program proposal.

Our catalog is publicly available, and we invite other members of the HWO community to build

¹⁶Funded through ADSPS22 grant No. 80NSSC23K1476.

¹⁷We address this in Chapter 4.

off of our work in future studies leading up to HWO and beyond. Ultimately, the subsequent work that follows from this catalog will play a critical role in the success of HWO and constraining the existence of life beyond the solar system.

Appendix

3.A Modifications to the EMSL

Our catalog contains most of the original information included in the EMSL. However, we identified a few errors or inconsistencies that we have corrected here. These are summarized as follows.

1. The EMSL contained an empty column (`eyes_lum`), which we have omitted here.
2. The star Toliman (α Cen B; HIP 71681) was originally flagged as a planet host in the EMSL. While an Earth-mass planet candidate orbiting this star was initially detected in radial velocity measurements of the system (Dumusque et al. 2012), subsequent analysis of the same data attributed the RV signal to the observational window function, thus ruling out α Cen Bb as a bona fide planet (Rajpaul et al. 2016). Therefore, in this work we have changed the `sy_pnum` column to 0 and the `sy_planets_flag` column to “N” for this star.
3. Mamajek and Stapelfeldt (2024) noted several stars in the EMSL that were previously reported to be binary, but are likely spurious (see their Appendix E). For example, the star 104 Tau (HIP 23835; WDS J05074+1839) was labeled as a “Dubious Double” in the Washington Double Star (WDS) Catalog notes, which could be attributed to a plate flaw, a positional typo in the original publication, or an optical double disappearing due to drastically different proper motions between the components (Mason et al. 2001). Lacaille 9352 (GJ 887; WDS J23059–3551) was also indicated as a binary in the WDS Catalog, but subsequent RV measurements ruled out a companion star while confirming two super-Earths in the system (Jeffers et al. 2020). HD 4628 (HIP 3765; WDS J00484+0517), HD 5015 (HIP 4151; WDS J00531+6107), ζ 2 Ret (HIP 15371; WDS J03182–6230), Chara (β CVn; HIP 61317; WDS J12337+4121), and 58 Oph (HIP 86736; WDS J17434–2141) also had previous indications of binarity in the literature, but were subsequently ruled out either by Mamajek and Stapelfeldt (2024) or other previous studies. For each of these stars, we have removed the spurious data from the `wdc_sep` and `wdc_deltamag` columns.
4. While the original EMSL included apparent V magnitudes and $B - V$ color indices, for convenience we have added a column with the individual B magnitudes. We also add a column for the B magnitude uncertainty, which we calculated by adding the V magnitude uncertainty and $B - V$ color uncertainty in quadrature.

3.B Additional Figures and Tables

This section contains additional figures and tables referenced in the main text. Figure 3.B1 shows the posterior distributions from the SED fit shown in Figure 3.8. Figure 3.B2 shows a static plot of key physical and observable properties of the stars considered in this work (an interactive version is available in the original online publication). Table 3.B1 contains the column definitions used in our catalog.

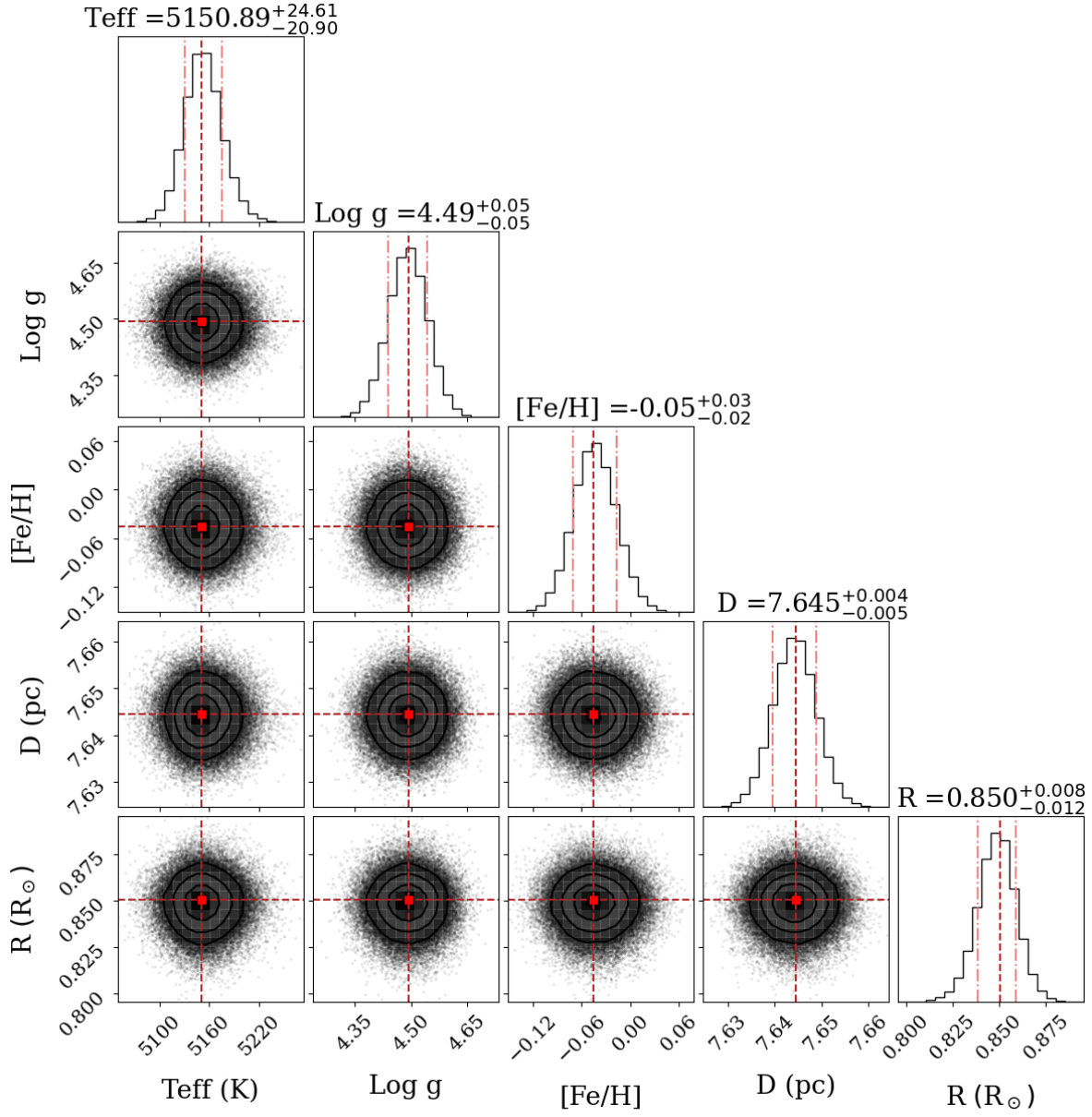


Figure 3.B1: Posterior distributions derived from the best-fit SED model for HD 10476 shown in Figure 3.8. The red dots show the median posterior values, while the vertical red lines in the marginalized posterior distributions show the 16th, 50th, and 84th percentile values.

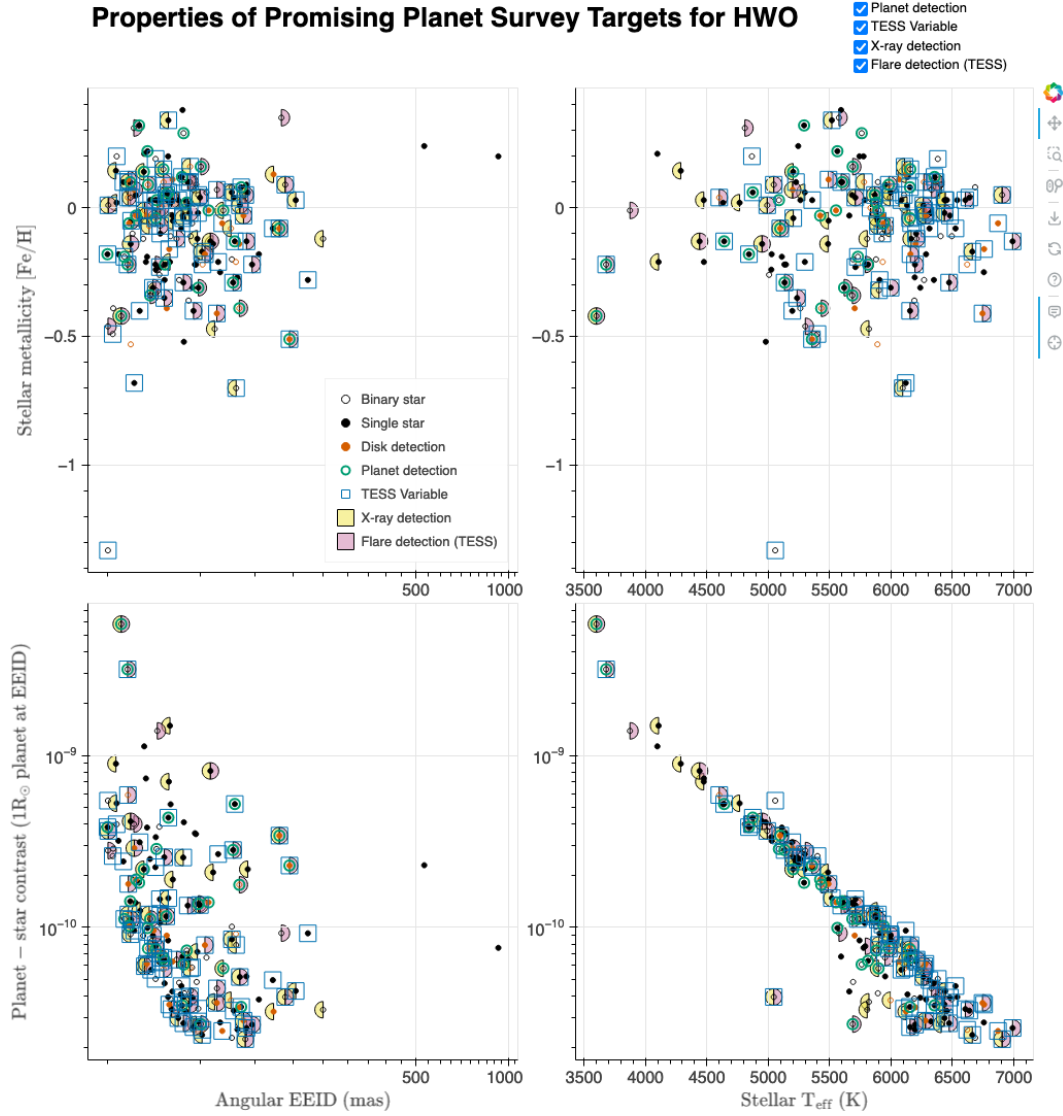


Figure 3.B2: Physical and observable properties of stars in our catalog. Starting from the upper left-hand panel and moving clockwise, the panels show stellar metallicity vs. angular EEID, stellar metallicity vs. effective temperature, estimated planet–star contrast ratio (in the R_c band) vs. effective temperature, and estimated planet–star contrast ratio vs. angular EEID. Different markers indicating stellar multiplicity, the presence of debris disks and planets, stellar variability, and flare and X-ray detections are defined in the legend. The bokeh.org interactive version online allows the user to highlight different subsets of the catalog, zoom and pan in the different, linked panels, and toggle tooltips and finder crosshairs on or off. (The interactive version of this figure originally appearing in Harada et al. (2024) is available at the publisher’s website.)

Column Name	Unit	Description	EMSL	References
TIC		TIC designation in the TESS Input Catalog. [tic_id]	Y	(86)
HIP		HIP designation in the Hipparcos Catalog. [hip_name]	Y	(26)
HIPComp		Component letters provided for when multiple stars are associated with the HIP entry (following CCDM, WDS, or SIMBAD). [hip_compname]	Y	(62)
HD		HD designation in the Henry Draper Catalog. [hd_name]	Y	(12)
HR		HR designation in the Bright Star Catalog, 5th Edition. [hr_name]	Y	(48)
GJ		GJ designation in the Preliminary Version of the Third Catalogue of Nearby Stars (CNS3) or Fifth Catalogue of Nearby Stars (CNS5). [gj_name]	Y	(36, 37)
Const		Constellation ID using Greek letters or numbers following the Bright Star Catalog, 5th Edition, or the Variable star ID from the General Catalogue of Variable Stars (GCVS), Version 5.1. The Greek letter abbreviations follow SIMBAD and the 3-letter constellation abbreviations follow IAU. [constellation]	Y	(48, 80)
Hostname		Common star ID, usually either (in order) IAU proper name, constellation ID (Greek letter, number, or variable star) written out in genitive form with the Greek letter written in the Latin alphabet, or ID from the HD, HR, or GJ catalogs. In some cases, the discovery ID is used for notable stars (e.g., Lacaille 8760). [hostname]	Y	(62)
Dist	pc	System distance d , calculated as $(1000 \text{ mas}/\varpi)$. [sy_dist]	Y	(62)
plx	mas	System parallax ϖ . [sy_plx]	Y	(3, 31, 32, 93)
e_plx	mas	Uncertainty in ϖ . [sy_plxerr]	Y	(3, 31, 32, 93)
r_plx		Reference bibcode for ϖ . [sy_plx.bibcode]	Y	(62)
RAdeg	deg	Right ascension (ICRS J2000). [ra]	Y	(62)
DEdeg	deg	Declination (ICRS J2000). [dec]	Y	(62)
Vmag	mag	Johnson V apparent magnitude. [sy_vmag]	Y	(24, 26, 45, 55, 64, 65, 91)
e_Vmag	mag	Uncertainty in the Johnson V apparent magnitude. [sy_vmagerr]	Y	(24, 26, 45, 55, 64, 65, 91)
r_Vmag		Reference bibcode for the Johnson V apparent magnitude. [sy_vmag.bibcode]	Y	(62)
B-V	mag	Johnson $B - V$ color index. [sy_bvmag]	Y	(23, 26, 32, 55, 64, 65)

e_B-V	mag	Uncertainty in the Johnson $B - V$ color index. [sy_bvmagerr]	Y	(23, 26, 32, 55, 64, 65)
r_B-V		Reference bibcode for the Johnson $B - V$ color index. [sy_bvmag_bibcode]	Y	(62)
Rcmag [†]	mag	Apparent Cousins R_c magnitude. [sy_rcmag]	Y	(6, 15, 33, 51, 73)
r_Rcmag [†]		Reference bibcode for the apparent Cousins R_c magnitude. [sy_rcmag_bibcode]	Y	(62)
SpT		Stellar spectral type. [st_spectype]	Y	(1, 2, 14, 16, 17, 21, 40, 41, 42, 43, 50, 53, 57, 58, 68, 90)
r_SpT		Reference bibcode for the spectral type. [st_spectype_bibcode]	Y	(62)
Teff	K	Stellar effective temperature T_{eff} . [st_teff]	Y	(13, 31, 32, 67, 70, 77, 82, 83, 86, 87, 92, 95, 99)
e_Teff	K	Uncertainty in T_{eff} . [st_tefferr]	Y	(13, 31, 32, 67, 70, 77, 82, 83, 86, 87, 92, 95, 99)
r_Teff		Reference bibcode for T_{eff} . [st_teff_bibcode]	Y	(62)
logLstar	dex	Logarithmic stellar bolometric luminosity normalized to solar, $\log_{10}(L_{\text{bol}}/L_{\odot})$. [st_lum]	Y	(9, 10, 11, 31, 32, 54, 85, 86, 92, 98)
e_logLstar	dex	Uncertainty in $\log_{10}(L_{\text{bol}}/L_{\odot})$. [st_lumerr]	Y	(9, 10, 11, 31, 32, 54, 85, 86, 92, 98)
r_logLstar		Reference bibcode for $\log_{10}(L_{\text{bol}}/L_{\odot})$. [st_lum_bibcode]	Y	(62)
Rstar	$R_{\odot}$	Stellar radius $R_{\star}$. [st_rad]	Y	(62)
theta	mas	Stellar angular diameter. [st_diam]	Y	(62)
Mstar	$M_{\odot}$	Stellar mass $M_{\star}$. [st_mass]	Y	(62)
met	dex	Stellar metallicity ($\log_{10}$ of the ratio of iron or average of metals to hydrogen, normalized to solar; generally either [Fe/H] or [M/H]). [st_met]	Y	(32, 35, 59, 60, 77, 83, 87, 92, 95, 98)
e_met	dex	Uncertainty in stellar metallicity. [st_meterr]	Y	(32, 35, 59, 60, 77, 83, 87, 92, 95, 98)
r_met		Reference bibcode for stellar metallicity. [st_met_bibcode]	Y	(62)
x_met		Type of stellar metallicity (generally either [Fe/H] or [M/H]). [st_metratio]	Y	(62)

logg	dex	Logarithmic stellar surface gravity, $\log g$, in cgs units. [st_logg]	Y	(4, 20, 30, 32, 77, 82, 83, 86, 87, 88, 92, 95, 98)
e_logg	dex	Uncertainty in $\log g$. [st_loggerr]	Y	(4, 20, 30, 32, 77, 82, 83, 86, 87, 88, 92, 95, 98)
r_logg		Reference bibcode for $\log g$. [st_logg_bibcode]	Y	(62)
logRHK	dex	Stellar Ca II H & K chromospheric activity index, $\log_{10}(R'_{\text{HK}})$. [st_log_rhk]	Y	(5, 8, 22, 38, 39, 42, 43, 44, 46, 52, 56, 61, 66, 69, 71, 76, 78, 79, 81, 84, 94, 96)
r_logRHK		Reference bibcode for $\log_{10}(R'_{\text{HK}})$. [st_log_rhk_bibcode]	Y	(62)
EEID-au	au	Earth equivalent instellation distance (EEID), calculated as $\sqrt{L_{\text{bol}}/L_{\odot}}$. [st_eei_orbsep]	Y	(62)
EEID-mas	mas	Angular EEID, calculated as EEID (in au) divided by d (in pc). [st_eei_angsep]	Y	(62)
EEID-per	days	Calculated orbital period for a planet at the EEID. [st_eei_orbper]	Y	(62)
ETWIN-bratio		Calculated planet-star brightness ratio, C , for a $1 R_{\odot}$ planet at EEID with an assumed geometric albedo of 0.2 at a phase angle of 91 degrees. [st_etwin_bratio]	Y	(62)
ETWIN-rcmag	mag	Calculated apparent Cousins R_c magnitude for a $1 R_{\odot}$ planet at EEID with an assumed geometric albedo of 0.2 at a phase angle of 91 degrees, calculated as $R_{c,\text{planet}} = R_{c,\star} - 2.5 \log_{10}(C)$. [st_etwin_rcmag]	Y	(62)
ETWIN-rvamp	cm s^{-2}	Calculated radial velocity amplitude of the star induced by a $1 M_{\oplus}$ planet at EEID. [st_etwin_rvamp]	Y	(62)
ETWIN-astamp	μas	Calculated astrometric amplitude of the star induced by a $1 M_{\oplus}$ planet at EEID. [st_etwin_astamp]	Y	(62)
WDS		WDS designation for multiple star systems in the Washington Double Star (WDS) Catalog. [wds_designation]	Y	(63)
WDSComp		Component for star in WDS multiple system. [wds_comp]	Y	(63)
WDS-Sep	arcsec	Angular separation between star and other WDS component. [wds_sep]	Y	(63)

WDS-deltamag	mag	Magnitude difference between target star and other WDS component star. [wds_deltamag]	Y	(63)
Disk-flag		Flag if star has an infrared excess indicative of a dust disk, as measured by IRAS, Spitzer, Herschel, WISE, or LBTI (Y=yes, N=no). [sy_disks_flag]	Y	(62)
r_Disk-flag		Reference bibcode for dust disk. [sy_disks_flag_bibcode]	Y	(62)
Planet-flag		Flag if star has one or more confirmed exoplanets in the NASA Exoplanet Archive (Y=yes, N=no). [sy_planets_flag]	Y	(62)
Nplanet		Number of confirmed exoplanets in the system from the NASA Exoplanet Archive. [sy_pnum]	Y	(62)
Tier		Tier group for target star (A, B, C). [target_group]	Y	(62)
Bmag	mag	Apparent Johnson B magnitude, derived from the 3 $B - V$ color index.	N	(89)
e_Bmag	mag	Uncertainty in the apparent Johnson B magnitude.	N	(89)
TIC-id		TIC ID number.	N	(89)
GaiaDR2		Cross-matched Gaia DR2 ID.	N	(86)
GaiaDR3		Cross-matched Gaia DR3 ID.	N	(34)
Gmag	mag	Gaia G magnitude.	N	(34)
e_Gmag	mag	Gaia G magnitude uncertainty.	N	(34)
BPmag	mag	Gaia G_{BP} magnitude.	N	(34)
e_BPmag	mag	Gaia G_{BP} magnitude uncertainty.	N	(34)
RPmag	mag	Gaia G_{RP} magnitude.	N	(34)
e_RPmag	mag	Gaia G_{RP} magnitude uncertainty.	N	(34)
AllWISE		Cross-matched AllWISE ID.	N	(34)
W1mag	mag	AllWISE W_1 magnitude.	N	(19)
e_W1mag	mag	AllWISE W_1 magnitude uncertainty.	N	(19)
W2mag	mag	AllWISE W_2 magnitude.	N	(19)
e_W2mag	mag	AllWISE W_2 magnitude uncertainty.	N	(19)
W3mag	mag	AllWISE W_3 magnitude.	N	(19)
e_W3mag	mag	AllWISE W_3 magnitude uncertainty.	N	(19)
W4mag	mag	AllWISE W_4 magnitude.	N	(19)
e_W4mag	mag	AllWISE W_4 magnitude uncertainty.	N	(19)
2MASS		Cross-matched 2MASS ID.	N	(34)
Jmag	mag	2MASS J magnitude.	N	(18)
e_Jmag	mag	2MASS J magnitude uncertainty.	N	(18)
Hmag	mag	2MASS H magnitude.	N	(18)
e_Hmag	mag	2MASS H magnitude uncertainty.	N	(18)
Ksmag	mag	2MASS K_s magnitude.	N	(18)
e_Ksmag	mag	2MASS K_s magnitude uncertainty.	N	(18)
Tycho2		Cross-matched Tycho-2 ID.	N	(34)
BTmag	mag	Tycho-2 B_T magnitude.	N	(49)

e_BTmag	mag	Tycho-2 B_T magnitude uncertainty.	N	(49)
VTmag	mag	Tycho-2 V_T magnitude.	N	(49)
e_VTmag	mag	Tycho-2 V_T magnitude uncertainty.	N	(49)
umag	mag	Strömgren u magnitude.	N	(72)
e_umag	mag	Strömgren u magnitude uncertainty.	N	(72)
vmag	mag	Strömgren v magnitude.	N	(72)
e_vmag	mag	Strömgren v magnitude uncertainty.	N	(72)
bmag	mag	Strömgren b magnitude.	N	(72)
e_bmag	mag	Strömgren b magnitude uncertainty.	N	(72)
ymag	mag	Strömgren y magnitude.	N	(72)
e_ymag	mag	Strömgren y magnitude uncertainty.	N	(72)
GALEX		Cross-matched GALEX identifier.	N	(89)
FUVmag	mag	GALEX FUV magnitude.	N	(7)
e_FUVmag	mag	GALEX FUV magnitude uncertainty.	N	(7)
NUVmag	mag	GALEX NUV magnitude.	N	(7)
e_NUVmag	mag	GALEX NUV magnitude uncertainty.	N	(7)
hypatia-Li	dex	Mean lithium abundance [Li/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Li*	dex	Lithium abundance uncertainty, calculated as the standard deviation of all [Li/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-Li		Number of [Li/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Li-min	dex	Minimum [Li/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Li-min		Literature reference for the minimum [Li/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Li-max	dex	Maximum [Li/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Li-max		Literature reference for the maximum [Li/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-C	dex	Mean carbon abundance [C/H] from the Hypatia Catalog.	N	(47)
e_hypatia-C*	dex	Carbon abundance uncertainty, calculated as the standard deviation of all [C/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-C		Number of [C/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-C-min	dex	Minimum [C/H] in the Hypatia Catalog.	N	(47)
r_hypatia-C-min		Literature reference for the minimum [C/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-C-max	dex	Maximum [C/H] in the Hypatia Catalog.	N	(47)
r_hypatia-C-max		Literature reference for the maximum [C/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-N	dex	Mean nitrogen abundance [N/H] from the Hypatia Catalog.	N	(47)

e_hypatia-N*	dex	Nitrogen abundance uncertainty, calculated as the standard deviation of all [N/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-N		Number of [N/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-N-min	dex	Minimum [N/H] in the Hypatia Catalog.	N	(47)
r_hypatia-N-min		Literature reference for the minimum [N/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-N-max	dex	Maximum [N/H] in the Hypatia Catalog.	N	(47)
r_hypatia-N-max		Literature reference for the maximum [N/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-O	dex	Mean oxygen abundance [O/H] from the Hypatia Catalog.	N	(47)
e_hypatia-O*	dex	Oxygen abundance uncertainty, calculated as the standard deviation of all [O/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-O		Number of [O/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-O-min	dex	Minimum [O/H] in the Hypatia Catalog.	N	(47)
r_hypatia-O-min		Literature reference for the minimum [O/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-O-max	dex	Maximum [O/H] in the Hypatia Catalog.	N	(47)
r_hypatia-O-max		Literature reference for the maximum [O/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Na	dex	Mean sodium abundance [Na/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Na*	dex	Sodium abundance uncertainty, calculated as the standard deviation of all [Na/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-Na		Number of [Na/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Na-min	dex	Minimum [Na/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Na-min		Literature reference for the minimum [Na/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Na-max	dex	Maximum [Na/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Na-max		Literature reference for the maximum [Na/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Mg	dex	Mean magnesium abundance [Mg/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Mg*	dex	Magnesium abundance uncertainty, calculated as the standard deviation of all [Mg/H] values from the Hypatia Catalog.	N	(47)

o_hypatia-Mg		Number of [Mg/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Mg-min	dex	Minimum [Mg/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Mg-min		Literature reference for the minimum [Mg/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Mg-max	dex	Maximum [Mg/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Mg-max		Literature reference for the maximum [Mg/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Al	dex	Mean aluminum abundance [Al/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Al*	dex	Aluminum abundance uncertainty, calculated as the standard deviation of all [Al/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-Al		Number of [Al/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Al-min	dex	Minimum [Al/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Al-min		Literature reference for the minimum [Al/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Al-max	dex	Maximum [Al/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Al-max		Literature reference for the maximum [Al/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Si	dex	Mean silicon abundance [Si/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Si*	dex	Silicon abundance uncertainty, calculated as the standard deviation of all [Si/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-Si		Number of [Si/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Si-min	dex	Minimum [Si/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Si-min		Literature reference for the minimum [Si/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Si-max	dex	Maximum [Si/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Si-max		Literature reference for the maximum [Si/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-P	dex	Mean phosphorus abundance [P/H] from the Hypatia Catalog.	N	(47)
e_hypatia-P*	dex	Phosphorus abundance uncertainty, calculated as the standard deviation of all [P/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-P		Number of [P/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-P-min	dex	Minimum [P/H] in the Hypatia Catalog.	N	(47)

r_hypatia-P-min		Literature reference for the minimum [P/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-P-max	dex	Maximum [P/H] in the Hypatia Catalog.	N	(47)
r_hypatia-P-max		Literature reference for the maximum [P/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-S	dex	Mean sulfur abundance [S/H] from the Hypatia Catalog.	N	(47)
e_hypatia-S*	dex	Sulfur abundance uncertainty, calculated as the standard deviation of all [S/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-S		Number of [S/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-S-min	dex	Minimum [S/H] in the Hypatia Catalog.	N	(47)
r_hypatia-S-min		Literature reference for the minimum [S/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-S-max	dex	Maximum [S/H] in the Hypatia Catalog.	N	(47)
r_hypatia-S-max		Literature reference for the maximum [S/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-K	dex	Mean potassium abundance [K/H] from the Hypatia Catalog.	N	(47)
e_hypatia-K*	dex	Potassium abundance uncertainty, calculated as the standard deviation of all [K/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-K		Number of [K/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-K-min	dex	Minimum [K/H] in the Hypatia Catalog.	N	(47)
r_hypatia-K-min		Literature reference for the minimum [K/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-K-max	dex	Maximum [K/H] in the Hypatia Catalog.	N	(47)
r_hypatia-K-max		Literature reference for the maximum [K/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Ca	dex	Mean calcium abundance [Ca/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Ca*	dex	Calcium abundance uncertainty, calculated as the standard deviation of all [Ca/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-Ca		Number of [Ca/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Ca-min	dex	Minimum [Ca/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Ca-min		Literature reference for the minimum [Ca/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Ca-max	dex	Maximum [Ca/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Ca-max		Literature reference for the maximum [Ca/H] measurement in the Hypatia Catalog.	N	(47)

hypatia-Fe	dex	Mean iron abundance [Fe/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Fe*	dex	Iron abundance uncertainty, calculated as the standard deviation of all [Fe/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-Fe		Number of [Fe/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Fe-min	dex	Minimum [Fe/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Fe-min		Literature reference for the minimum [Fe/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Fe-max	dex	Maximum [Fe/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Fe-max		Literature reference for the maximum [Fe/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Ni	dex	Mean nickel abundance [Ni/H] from the Hypatia Catalog.	N	(47)
e_hypatia-Ni*	dex	Nickel abundance uncertainty, calculated as the standard deviation of all [Ni/H] values from the Hypatia Catalog.	N	(47)
o_hypatia-Ni		Number of [Ni/H] measurements in the Hypatia Catalog.	N	(47)
hypatia-Ni-min	dex	Minimum [Ni/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Ni-min		Literature reference for the minimum [Ni/H] measurement in the Hypatia Catalog.	N	(47)
hypatia-Ni-max	dex	Maximum [Ni/H] in the Hypatia Catalog.	N	(47)
r_hypatia-Ni-max		Literature reference for the maximum [Ni/H] measurement in the Hypatia Catalog.	N	(47)
Nsedpoints		Number of photometric points used to compute SED fit with ARIADNE (Vines and Jenkins 2022).	N	(89)
SEDModel		Name of SED model favored by Bayesian model selection.	N	(89)
ModelProb		Probability of the favored SED model, derived from the Bayesian evidence.	N	(89)
Teff-SED	K	Stellar effective temperature T_{eff} derived from SED Bayesian model averaging with ARIADNE.	N	(89)
e_Teff-SED	K	Lower T_{eff} uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
E_Teff-SED	K	Upper T_{eff} uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
Rstar-SED	$R_{\odot}$	Stellar radius $R_{\star}$ derived from SED Bayesian model averaging with ARIADNE.	N	(89)
e_Rstar-SED	$R_{\odot}$	Lower $R_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)

E_Rstar-SED	$R_{\odot}$	Upper $R_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
Mstar-SED1	$M_{\odot}$	Stellar mass $M_{\star}$ (from $\log g$) derived from SED Bayesian model averaging with ARIADNE.	N	(89)
e_Mstar-SED1	$M_{\odot}$	Lower gravitational $M_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
E_Mstar-SED1	$M_{\odot}$	Upper gravitational $M_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
Mstar-SED2	$M_{\odot}$	Stellar mass $M_{\star}$ (from isochrones) derived from SED Bayesian model averaging with ARIADNE.	N	(89)
e_Mstar-SED2	$M_{\odot}$	Lower isochronal $M_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
E_Mstar-SED2	$M_{\odot}$	Upper isochronal $M_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
Lstar-SED	$L_{\odot}$	Stellar luminosity $L_{\star}$ derived from SED Bayesian model averaging with ARIADNE.	N	(89)
e_Lstar-SED	$L_{\odot}$	Lower $L_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
E_Lstar-SED	$L_{\odot}$	Upper $L_{\star}$ uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
Age-SED	Gyr	Stellar age (from isochrones) derived from SED Bayesian model averaging with ARIADNE.	N	(89)
e_Age-SED	Gyr	Lower age uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
E_Age-SED	Gyr	Upper age uncertainty (1σ), derived from SED Bayesian model averaging.	N	(89)
TESSFlare		Flag indicating whether stellar flares have been detected for this target with TESS. (1=yes, 0=no).	N	(89)
Nsectors		Number of TESS sectors with two-minute cadence observations of the target.	N	(89)
FlareCount		Number of stellar flares detected during the first 39 (or 30) TESS sectors.	N	(74, 97)
FlareRate	s^{-1}	Estimated stellar flare rate, calculated as the number of flares detected divided by the TESS observational baseline for the target.	N	(89)
Ampmax		Maximum relative flare amplitude.	N	(74, 97)
Emaxx	erg	Maximum estimated flare energy.	N	(74, 97)
r_FlareRate		Reference bibcode for TESS flare rate.	N	(89)

XrayFlareFlag		X-ray flare detected in the XMM-Newton serendipitous source catalogue (“Y” or “N”).	N	(75)
TESSVar		Flag indicating whether this target is variable in TESS photometry (1=yes, 0=no).	N	(89)
TESSModel		Best model from the 19 variability analysis; can be Single-sinusoidal (1sin), Double-sinusoidal (2sin), or Auto-Correlation Function (acf).	N	(27)
TESSSec		TESS Sector number from which this variability analysis was extracted; sp indicates the short-period periodogram search (0.01–1.5 days) was preferred.	N	(27)
P1	days	Measured photometric variability period for the first sinusoidal component.	N	(27)
P2	days	Measured photometric variability period for the second sinusoidal component.	N	(27)
e_P1	days	Uncertainty in the photometric variability period for the first sinusoidal component.	N	(27)
e_P2	days	Uncertainty in the photometric variability period for the second sinusoidal component.	N	(27)
A1	ppm	Flux amplitude of photometric variability for the first sinusoidal component.	N	(27)
A2	ppm	Flux amplitude of photometric variability for the second sinusoidal component.	N	(27)
e_A1	ppm	Uncertainty in the flux amplitude of photometric variability for the first sinusoidal component.	N	(27)
e_A2	ppm	Uncertainty in the flux amplitude of photometric variability for the second sinusoidal component.	N	(27)
VSX-flag		Flag indicating whether this target is included in the AAVSO VSX Catalog (1=yes, 0=no).	N	(89)
VSX-name		Source name in the AAVSO VSX Catalog.	N	(89)
VSX-status		Source variability status in the AAVSO VSX Catalog (“V”=variable, “S”=suspected variable).	N	(89)
VSX-0ID		URL link to the VSX entry for this source.	N	(89)
Xray-flag		Flag indicating whether this target has a previous X-ray detection (1=yes, 0=no).	N	(89)
morxv2		Object ID from the literature adopted in the MORX Catalog.	N	(28, 29)
Xraypct		The calculated percent likelihood that the shown X-ray detection(s) is associated with this optical object.	N	(28, 29)

starpct		The calculated percentage likelihood that the X-ray associated object is a star.	N	(28, 29)
CX-ID		Chandra X-ray detection ID, if any.	N	(28, 29)
XMM-ID		XMM-Newton X-ray detection ID, if any.	N	(28, 29)
Swift-ID		SWIFT X-ray detection ID, if any.	N	(28, 29)
OtherXID		ROSAT or XMM-Slew X-ray detection ID, if any.	N	(28, 29)

Notes. The column labels used in this table attempt to conform the original column labels used in the EMSL as published on the NASA Exoplanet Archive with the standards used for the majority of the additional source material, much of which is from VizieR and thus follows the VizieR column-labeling system. When a column label differs from the original source, the original label is given in square [] brackets.

[†] Mamajek and Stapelfeldt (2024) either adopted Cousins R_c magnitudes from the literature or estimated them based on Gaia EDR3 G and G_{RP} photometry or by adopting an intrinsic $V - R_c$ color for the star’s spectral type.

* If only a single abundance measurement was identified in the catalog, we provide an estimate of the uncertainty as the median [Fe/H] uncertainty from the entire sample (0.065 dex).

References. (1) Abt (1981); (2) Abt (2009); (3) Akeson et al. (2021); (4) Anders et al. (2019); (5) Baliunas et al. (1996a); (6) Bessel (1990); (7) Bianchi et al. (2017); (8) Boro Saikia et al. (2018); (9) Boyajian et al. (2012); (10) Boyajian et al. (2013); (11) Brown et al. (2022); (12) Cannon and Pickering (1993); (13) Casagrande et al. (2011); (14) Corbally (1984); (15) Cousins (1980); (16) Cowley et al. (1967); (17) Cowley (1976); (18) Cutri et al. (2003); (19) Cutri et al. (2021) (20) David and Hillenbrand (2015); (21) Dieterich et al. (2012); (22) Duncan et al. (1991); (23) Eggen (1965); (24) Eggenberger et al. (2008); (25) Egan and Price (1997); (26) ESA (1997); (27) Fetherolf et al. (2023); (28) Flesch (2016); (29) Flesch (2024); (30) Fuhrmann (2008); (31) Gaia Collaboration et al. (2018); (32) Gaia Collaboration (2022a); (33) Gaia Collaboration (2022b); (34) Gaia Collaboration et al. (2023); (35) Gáspár et al. (2016); (36) Gliese and Jahrei (1991); (37) Golovin et al. (2023); (38) Gomes da Silva et al. (2021); (39) Gondoin (2020); (40) Gray (1989); (41) Gray et al. (2001); (42) Gray et al. (2003); (43) Gray et al. (2006); (44) Hall et al. (2007); (45) Hauck and Mermilliod (1998); (46) Henry et al. (1996); (47) Hinkel and Unterborn (2018); (48) Hoffleit and Jaschek (1991); (49) Hg et al. (2000a); (50) Houk and Cowley (1975); (51) Huang et al. (2015); (52) Isaacson and Fischer (2010); (53) Keenan and McNeil (1989); (54) Kervella et al. (2017); (55) Kharchenko (2001); (56) King et al. (2003); (57) Kirkpatrick et al. (1991); (58) Lee (1984); (59) Lindgren and Heiter (2017); (60) Luck and Heiter (2005); (61) Maldonado et al. (2010); (62) Mamajek and Stapelfeldt (2024); (63) Mason et al. (2001); (64) Mermilliod (1997); (65) Mermilliod et al. (1997); (66) Meunier et al. (2022); (67) Montes et al. (2018); (68) Morgan and Keenan (1973); (69) Murgas et al. (2013); (70) Newton et al. (2015); (71) Pace (2013); (72) Paunzen (2015a); (73) Pickles and Depagne (2010); (74) Pietras et al. (2022); (75) Pye et al. (2015); (76) Radick et al. (2018); (77) Ramrez et al. (2013); (78) Rocha-Pinto et al. (2004); (79) Saffe et al. (2005); (80) Samus’ et al. (2017); (81) Schrder et al. (2009); (82) Schweitzer et al. (2019); (83) Soubiran et al. (2022); (84) Stanford-Moore et al. (2020); (85) Stassun et al. (2018); (86) Stassun et al. (2019); (87) Takeda et al. (2005); (88) Takeda et al. (2007); (89) This work; (90) Torres et al. (2006); (91) Twarog and Anthony-Twarog (1995); (92) Valenti and Fischer (2005); (93) van Leeuwen (2007); (94) Vican (2012); (95) Woolf and Wallerstein (2005); (96) Wright et al. (2004); (97) Yang et al. (2023); (98) Yee et al. (2017); (99) Zorec and Royer (2012).

(Only a portion of this table is shown here to demonstrate its form and content. A machine-readable version of the full table in Harada et al. (2024) is available at the publisher’s website.)

Table 3.B1: Catalog Column Definitions.

Chapter 4

Planetary System Architectures in the Solar Neighborhood

*A previous version of this chapter was published in: Harada, C. K., Dressing, C. D., Turtelboom, E. V., Kane, S. R., Blunt, S., Dietrich, J., Hinkel, N. R., Li, Z., Mamajek, E., Rice, M., Tuchow, N. W., Wittenmyer, R. A., Chin, C., Fernandez, A., Kulkarni, S., Lin, E., Liu, N., Liu, R., Nathan, A., & Zbriger, A., 2025, *The Astronomical Journal*, 170(6), 343.*



A goal of the future Habitable Worlds Observatory (HWO) is to directly image and spectroscopically characterize true Earth-analogs. However, if a large fraction of HWO target stars host unknown dynamically disruptive giant planets in their habitable zones (HZs), then additional targets that are farther away will need to be surveyed, potentially requiring a larger-aperture telescope and a coronagraph with a smaller inner working angle. Therefore, the sooner we constrain the presence of massive planets orbiting potential HWO target stars, the easier and less costly it will be to adjust key aspects of HWO's architecture. In this work, we uniformly analyze over 153,000 public radial velocity (RV) observations of 120 potential HWO target stars to derive mass limits on planetary companions. The RVs were measured by 23 spectrographs located at 15 observatories around the world, with the first observations going back to 1987. Based on empirical search completeness tests, we determine that undetected Jupiter-mass (Saturn-mass) planets may be hiding in up to 38% (53%) of the HZs of targets in the ExEP Mission Star List. The median mass sensitivity limit in the middle of the conservative HZ is approximately $48 M_{\oplus}$. We also provide updated parameters for 53 known companions, and we detect at least 26 additional RV signals corresponding to stellar activity and 4 signals that are planet candidates. We note that 44 of the ExEP stars lack substantial RV monitoring history, and we advocate for community-coordinated observing campaigns of these stars using moderate-precision RV facilities.

4.1 Introduction

To date, over 5900 exoplanets have been discovered in at least 4300 unique planetary systems.¹ Despite this growing number of planet discoveries, astronomers have yet to achieve a complete census of the exoplanet population. Nonetheless, the observed population of exoplanets clearly demonstrates that many planetary systems bear little resemblance to what we see in our own solar system (e.g., Mayor et al. 2011; Howard et al. 2012; Wright et al. 2012; Fressin et al. 2013; Petigura et al. 2013b; Dressing and Charbonneau 2015; Fulton et al. 2017; Petigura et al. 2018; Duck et al. 2021; Gan et al. 2023). This staggering diversity has led to many outstanding questions concerning the uniqueness of our solar system in terms of its planetary properties, formation and evolutionary history, and habitability.

The current census of exoplanets has depended heavily on the workhorse transit and radial velocity (RV) detection methods, which are both biased toward large (massive) planets orbiting close in to their host stars. However, multidecade RV searches have begun to reach the long observational baselines required to detect more distant giant planets, thus shedding light on the population of cooler outer planets (e.g., Howard and Fulton 2016; Fernandes et al. 2019; Wittenmyer et al. 2020; Fulton et al. 2021; Rosenthal et al. 2021 hereafter R21; Laliotis et al. 2023 hereafter L23). With decades of an observational baseline, we can start to piece together the full architectures of planetary systems and fill in our incomplete understanding of planetary demographics. These observations are also key to understanding the dynamical past, present, and future of planetary systems, and constraining whether additional planets may be present (e.g., Barnes and Raymond 2004; Kane 2015, 2023; Kane and Blunt 2019; Dietrich and Apai 2021; Dietrich et al. 2022).

Future observational facilities will continue to improve our sensitivity to ever smaller and longer-period planets. One of the fundamental goals driving these advancements is detecting and precisely measuring Earth-like planets orbiting in the habitable zones (HZs) of Sun-like stars, including those that may be habitable (National Academies of Sciences, and Medicine, Engineering 2021). For example, new generations of extreme precision radial velocity (EPRV) instruments have already begun intensive searches for terrestrial-mass planets whose sub-meter-per-second signals were too small for previous generations of instruments (e.g., Brewer et al. 2020; Crass et al. 2021; Gupta et al. 2021, 2025; Newman et al. 2023). Future detections and characterization of potentially Earth-like planets, when appropriately contextualized by a more complete census of exoplanets, better theories of planet formation, and robust knowledge of the planets' astrophysical environments, will revolutionize astronomy and the human condition. Such an undertaking will require synergy between demonstrated techniques that have formed our broader understanding of planetary astrophysics over the last few decades and new innovations like EPRV.

However, while EPRV is an important pathway toward identifying potentially Earth-like exoplanets and measuring their masses, no single detection technique is yet capable of measuring planetary habitability. High-fidelity spectroscopic measurements of terrestrial planet atmospheres will be essential for robustly characterizing global biospheres and ruling out false-positive claims

¹NASA Exoplanet Archive, accessed 2025 August 20; <https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PS>.

of inhabitation. Such observations will likely only be possible with future high-contrast direct-imaging (DI) facilities capable of measuring the reflected-light spectra of Earth-size exoplanets, with complementary ground- and space-based observations providing the context clues necessary for interpretation.

The Habitable Worlds Observatory (HWO) is NASA’s flagship mission concept for a large ultraviolet/optical/near-infrared (UV/O/NIR) space telescope with high-contrast ($\sim 10^{-10}$) DI instrumentation. Slated for the 2040s, HWO will be capable of imaging and measuring the reflectance spectra of Earth-like exoplanets in the HZs of nearby bright stars. With its exquisite sensitivity, broad wavelength coverage, and starlight suppression technology, HWO will not only constrain the prevalence of potentially habitable and inhabited extrasolar worlds but also enable revolutionary astrophysics in star formation, galactic evolution, cosmology, and the solar system (C. D. Dressing et al. 2026, in preparation). Key technologies and strategies for HWO are actively being developed (e.g., Vaughan et al. 2023; Stark et al. 2024a,b), and provisional target lists of bright nearby stars for the exoEarth survey are being constructed (Harada et al. 2024; Mamajek and Stapelfeldt 2024; Tuchow et al. 2024, 2025). As the HWO mission concept and target lists continue to mature, a robust understanding of likely exoEarth survey target stars is necessary to inform exoplanet yield calculations, which in turn enable reliable trade studies of potential HWO architecture options. Furthermore, precursor and preparatory science for the HWO target stars will be essential for accurately interpreting biosignature observations and placing worlds that HWO discovers in astrophysical context (e.g., Batalha et al. 2019; Damiano et al. 2025).

Previously, in Chapter 3 (Harada et al. 2024), we outlined a precursor science project for HWO that aims to characterize the most promising targets for a DI search for exoEarths. We compiled and analyzed archival data of 164 nearby FGKM stars from the Exoplanet Exploration Program (ExEP) Mission Star List² (EMSL; Mamajek and Stapelfeldt 2024), then synthesized key target star information in the System Properties and Observational Reconnaissance for Exoplanet Studies with HWO (SPORES-HWO) Catalog. The catalog includes fundamental stellar properties, multiband photometry, chemical abundances, optical flare rates, and photometric variability. In this chapter, we provide a comprehensive review and analysis of precursor RV observations of potential HWO exoEarth survey targets. Specifically, we combine and uniformly reanalyze all of the publicly available precision RV measurements of the 164 SPORES-HWO stars from the past ~ 35 yr in order to (1) search for new planet candidates (PCs), (2) refine orbits and planet parameters of known planets, (3) identify false-positive signals, and (4) empirically measure the search completeness to derive meaningful limits on companions to potential HWO target stars.

Past work to quantify RV mass limits on companions for potential DI target stars has suggested that planets as large as Saturn or larger can be undetectable in many nearby systems (e.g., Howard and Fulton 2016; L23). Understanding the current RV landscape for potential HWO target stars is particularly important for prioritizing dynamically viable target systems, as prior knowledge of any RV-detected massive planets in the HZ can rule out the long-term stability of any potential Earth-like worlds (e.g., Kane and Burt 2024; Kane et al. 2024). Furthermore, sibling planets to exoEarths

²https://exoplanetarchive.ipac.caltech.edu/docs/2645_NASA_ExEP_Target_List_HWO_Documentation_2023.pdf

revealed by RVs may themselves provide clues to habitability by way of their migration history and ability to scatter volatile-rich debris inward to the HZ from beyond the snow line (Raymond et al. 2004, 2008; Meadows and Barnes 2018; Kane and Wittenmyer 2024).

By searching for new PCs, refining orbits and planet properties of known planets, and measuring the RV search completeness, we can accurately simulate the types of planets HWO will detect, and place limits on their masses. For example, if planets above a certain mass can be ruled out with RV data obtained now, any planets imaged with HWO in the future must be less massive and hence more likely to be habitable. Knowledge of the current RV sensitivity also informs the requirements for HWO’s onboard astrometry, which will determine the dynamical masses of new planets discovered by the survey. Lastly, a precursor RV survey supports the broader exoplanet science themes of HWO as well as the general exoplanet community. In addition to exoEarths, HWO will detect a statistical sample of cool Jovian and Neptune-like planets, and constraining the masses of these planets now prepares us for interpreting the atmospheric spectra that HWO will measure.

The rest of this chapter is organized as follows. In Section 4.2, we provide an overview of the target sample considered in this study. In Section 4.3, we summarize the RVs and stellar activity (SA) data we obtained for the target stars, in addition to the community science project that was created to handle the large amount of data. Then, in Section 4.4, we describe the analysis of the RVs and SA data and the injection-recovery tests used to measure search completeness. In Section 4.5, we present the RV search and completeness test results and highlight six systems with new signal detections. In Section 4.6, we discuss how our results add to previous work, improve our sensitivity to planets both inside and outside the HZs of nearby stars, and set the stage for future observing efforts to better understand the planetary systems around potential HWO target stars. Finally, we summarize our main conclusions in Section 4.7.

4.2 Target List

Several potential target lists for future space-based DI survey missions have recently been developed. For HWO, the NASA ExEP³ recently published a provisional list of 164 target stars for the HWO exoEarth survey (Mamajek and Stapelfeldt 2024). The EMSL was adapted and refined from the preliminary mission study target lists from the Large UV/Optical/IR Surveyor (LUVOIR; The LUVOIR Team 2019) and Habitable Exoplanet Observatory (Gaudi et al. 2020). In brief, the EMSL contains 66 F-type stars, 55 G-type stars, 40 K-type stars, and 3 M-type stars. The majority of stars are on the main sequence, but a few subgiant stars are also included (four stars have low surface gravity measurements, $\log g < 4.0$).

In addition to the EMSL, other much larger lists of potential HWO targets have been created. For example, the Habitable Worlds Observatory Preliminary Input Catalog (HPIC) contains $\sim 13,000$ possible HWO targets (Tuchow et al. 2024). The HPIC is descended from the Transiting Exoplanet Survey Satellite (TESS) and Gaia DR3 catalogs, and, in contrast to the EMSL, is more

³<https://exoplanets.nasa.gov/exep/about/overview/>

useful for yield calculations, which require large input catalogs in order to simulate the science output of possible observatory architectures (Stark et al. 2024b).

While both the EMSL and HPIC are useful in different aspects of precursor science for HWO, the stars in the shorter EMSL were selected to have the most easily accessible HZs for a variety of HWO architectures. Therefore, these stars are considered a high-priority short list of potential HWO targets.⁴ Previously, in Chapter 3 (Harada et al. 2024) we synthesized information about these high-priority HWO targets in the SPORES-HWO Catalog,⁵ which includes fundamental stellar properties, multiband photometry, chemical abundances, optical variability, and high-energy emission. Here, we continue to focus on the 164 EMSL (or SPORES-HWO) stars, as this sample represents the most likely stars to be observed with HWO regardless of its final architecture.

4.3 Data

In this section, we summarize the sources of the RV data and SA indicators analyzed in this study and discuss how the data were collected. In brief, we acquired archival RV measurements and SA indicators for all 164 SPORES-HWO stars, in all cases where such data were publicly accessible. For subsequent analysis, we required that each star have at least 20 unique nights of public RV observations. Of the 164 stars in the sample, we identified 120 stars (73%) with at least 20 nights of public RV observations. An additional 21 stars have at least one RV observation, while the remaining 23 stars had no publicly available RV data.

A total of 153,902 individual RV measurements (35,794 RVs binned to nightly intervals) were obtained from 40 literature sources. We also compiled 43,649 binned SA indicator measurements, including S -index, H -index, R'_{HK} , $H\alpha$ equivalent width (EW), and the cross correlation function (CCF) full width at half-maximum (FWHM) and bisector inverse slope (BIS). The data were originally collected by 23 different spectrographs located at 15 observatories across the globe. Considering all targets and all spectrographs, the observations span a total of over 36 yr from 1987 June to 2023 December, the product of the tremendous efforts of hundreds of observers over the entire history of the field of exoplanets.

Figure 4.1 shows the positions of the targets on sky and the locations of the observatories used to collect the RVs analyzed in this study. A tabulated summary of the data from each spectrograph is given in Table 4.1. Keplerian signals identified in the RVs are discussed in Section 4.5 and summarized in Table 4.2, and a summary of the data collected for each target star is given in Table 4.A1 in the appendix of this chapter. The following subsections provide further details regarding how these data were collected and processed for the purpose of this study.

The final data set for all target stars, including all unbinned RV and SA indicator measurements,

⁴While the EMSL is an important starting point for HWO precursor science, we note that the scope of the list is limited by some assumptions regarding the notional observatory design (Mamajek and Stapelfeldt 2024). We caution that the EMSL and SPORES-HWO Catalog should not be interpreted as final target lists for the HWO exoEarth survey, but rather as target lists for HWO precursor science studies.

⁵<https://calebharada.github.io/spores/>

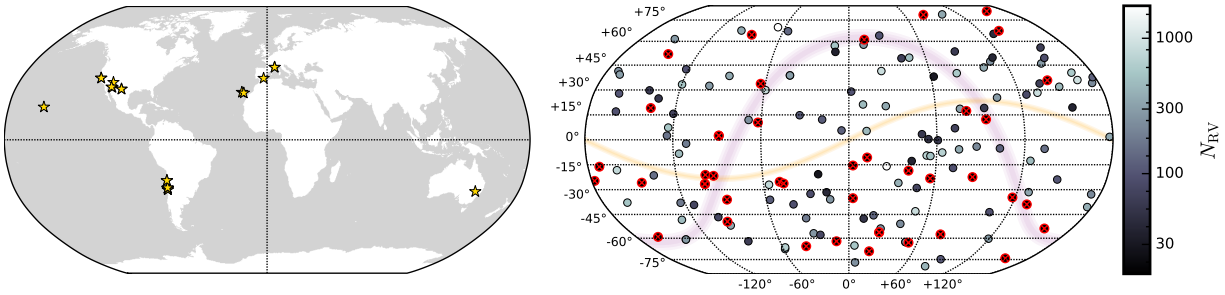


Figure 4.1: Left: locations of the 20 telescopes at 15 different observatories used to measure the RV data analyzed in this work (see Table 4.A2 for observatory details). Right: International Celestial Reference System (J2000) coordinates of the target stars in this study with the number of public RV epochs indicated logarithmically by the color bar. The 44 (of 164) targets with fewer than 20 RV epochs are indicated by red “ $\otimes$ ” symbols—these targets were excluded from the subsequent RV analysis. The ecliptic and galactic planes are shown for reference in yellow and purple, respectively.

is published and available for download on Zenodo.⁶ In future work, we will also move the data to an online database where users can download data and upload new observations as they become available.

Data Sources

We compiled RV observations from a wide variety of sources in order to maximize the completeness of our search. We include observations beginning from the earliest generation of échelle spectrographs that enabled some of the first detections of exoplanets around main-sequence stars (e.g., ELODIE on the 1.93 m Telescope at the Observatoire de Haute-Provence (OHP) and Hamilton on the 3 m Shane Telescope at Lick Observatory), in addition to next-generation instruments with improved RV precision (e.g., High Accuracy Radial Velocity Planet Searcher, hereafter HARPS, on the ESO 3.6 m Telescope at La Silla Observatory and Planet Finder Spectrograph, hereafter PFS, on the 6.5 m Magellan II Telescope at Las Campanas Observatory), and current cutting-edge EPRV instruments with the highest available precision (e.g., Extreme Precision Spectrograph, hereafter EXPRES, on the 4.3 m Lowell Discovery Telescope at Lowell Observatory and NN-EXPLORE Exoplanet Investigations with Doppler Spectroscopy, hereafter NEID, on the 3.5 m Wisconsin-Indiana-Yale-NOIRLab, hereafter WIYN, Telescope at Kitt Peak National Observatory). A complete list of the 15 observatories and 23 spectrographs is provided in Table 4.A2 in the appendix of this chapter.

Because each spectrograph was designed independently, often many years apart, each one has a unique set of characteristics that result in different levels of RV precision. For example, spectral resolving power, wavelength range, throughput, thermal stability, and wavelength calibration method are all factors that may vary from instrument to instrument. Some of the key spectrograph

⁶doi:10.5281/zenodo.17058228

Instrument	# RVs	# SAI	First Obs.	Last Obs.	Span (yr)	Reference(s)
AFOE	65	0	1994-09-22	2001-09-07	7.0	Naef et al. (2003); Butler et al. (1997)
CARMENES	316	0	2016-01-08	2020-01-10	4.0	Stock et al. (2020); Šubjak et al. (2023)
CES-LC	767	0	1992-11-03	1998-04-04	5.4	Zechmeister et al. (2013); Endl et al. (2001)
CES-VLC	383	0	1999-11-21	2006-05-24	6.5	Zechmeister et al. (2013)
CHIRON	181	0	2011-03-10	2013-05-25	2.2	Zhao et al. (2018)
CORALIE-07	98	48	2007-06-10	2014-07-17	7.1	Boehle et al. (2019); Barbato et al. (2023); Damasso et al. (2020); Marmier et al. (2013)
CORALIE-14	250	0	2014-11-13	2021-09-09	6.8	Boehle et al. (2019); Barbato et al. (2023); Damasso et al. (2020)
CORALIE-98	322	293	1998-07-27	2007-01-21	8.5	Boehle et al. (2019); Barbato et al. (2023); Naef et al. (2001); Mayor et al. (2004); Damasso et al. (2020); Marmier et al. (2013)
CTIO-ES	286	0	2008-08-11	2010-05-18	1.8	Zhao et al. (2018)
ELODIE	263	66	1994-04-24	2004-06-08	10.1	Naef et al. (2003); Moutaka et al. (2004); Naef et al. (2004)
ESPRESSO	108	148	2018-09-06	2023-03-25	4.5	Damasso et al. (2020); Nari et al. (2025)
EXPRES	246	416	2018-04-28	2023-05-09	5.0	Zhao et al. (2022); Roettenbacher et al. (2022); Brewer et al. (2023); Cabot et al. (2021)
HARPS-North	23	91	2012-08-09	2014-03-29	1.6	Bourrier et al. (2018); Motalebi et al. (2015)
HARPS-post	1,804	6,963	2015-05-31	2021-12-29	6.6	Trifonov et al. (2020)
HARPS-pre	5,348	20,128	2003-10-24	2015-05-16	11.6	Trifonov et al. (2020); Brems et al. (2019)
HIRES-post	5,444	9,422	2004-08-20	2020-03-10	15.6	Butler et al. (2017); Hirsch et al. (2021); R21
HIRES-pre	772	765	1996-07-11	2004-07-21	8.0	Butler et al. (2017); R21
HRS	243	0	2003-10-15	2008-07-24	4.8	Wittenmyer et al. (2009); McArthur et al. (2010); Endl et al. (2012)
Hamilton	4,908	0	1987-06-11	2020-03-08	32.7	Fischer et al. (2014); R21
Levy	7,514	147	2013-06-20	2021-04-27	7.9	L23; R21; Hirsch et al. (2021)
NEID	157	0	2021-01-03	2023-12-13	2.9	Giovannazzi et al. (2025a); Gupta et al. (2025)
PFS-post	113	108	2018-02-07	2021-05-26	3.3	L23
PFS-pre	364	323	2011-01-26	2017-04-19	6.2	L23
SONG	328	0	2015-04-03	2017-03-06	1.9	Šubjak et al. (2023)
SOPHIE	2,358	2,790	2006-08-30	2023-05-31	16.8	Moutaka et al. (2004); Díaz et al. (2019); Bourrier et al. (2018)
Tull	336	126	1998-07-15	2014-02-08	15.6	Wittenmyer et al. (2009); Benedict et al. (2006); Wittenmyer et al. (2007); Endl et al. (2016, 2012)
UCLES	2,794	1,815	1998-01-16	2015-11-22	17.8	L23; Butler et al. (2006)
UVES	3	0	2004-09-24	2017-08-28	12.9	Feng et al. (2019)

Notes. Data have been binned to nightly intervals. Stellar activity indicators (SAI).

Table 4.1: Overview of RV Data Compiled from the Literature.

and observatory properties for the instruments used in this study are summarized in Table 4.A2 in the appendix, but we point the reader to the references therein for more detailed discussion of each spectrograph.

We note that some spectrographs have undergone one or more significant upgrades since becoming operational. For example, the High Resolution Échelle Spectrometer (HIRES) instrument on the 10 m Keck I Telescope at Keck Observatory underwent a significant upgrade in 2004 when a new CCD was installed, improving the typical RV precision from $\sim 4\text{--}5\text{ m s}^{-1}$ to $\sim 1\text{--}2\text{ m s}^{-1}$ (Butler et al. 2017). Similarly, HARPS underwent a significant upgrade in 2015 when the optical fibers were replaced (Lo Curto et al. 2015). It is important to note that changes to the detector or fiber-optic cables can introduce systematic offsets between the preupgrade and postupgrade RV data, biasing potential planet detections and orbit fits. We therefore treat data before and after such upgrades as independent data sets, as if the data were measured by separate instruments. We have indicated this by appending either “-pre” or “-post” or the year of the upgrade after the instrument name (e.g., “HIRES-pre,” “HIRES-post,” “CORALIE-98,” “CORALIE-07”)

In general, we gathered all publicly available RV measurements that met the following basic criteria: (1) were timestamped with precision better than 0.5 day, (2) included an uncertainty value, and (3) were measured with a precision better than a few tens of meters per second. We only considered published or well-documented data sets that included the final reduced RV measurements (i.e., we did not reduce any raw spectra in this work). The next subsection details the steps we followed to locate and organize all the RV data.

The SPORES-HWO RV Hunters Community Science Project

Identifying and organizing all of the public RV measurements of the 164 SPORES-HWO target stars proved to be a nontrivial task. Completeness and consistency were two major challenges of this process. Because the targets are bright ($V < 8$), many have historically been ideal targets for multiple RV exoplanet surveys. Fortunately, this has led to an extensive volume of RV data in the literature for 164 stars. However, this inherently leads to difficulty in determining just how much data exist and whether it is accessible. In other words, although we desire as many RV measurements from the literature as possible, we do not know a priori how much data to expect any given target to have or where to find it.

For example, RVs for some targets may be part of a large, easily accessible database, while for others the RVs may only be available as a formatted table within a single publication. Making matters more difficult is the fact that data sets from different sources are heterogeneous, often differing substantially in terms of which types of metadata are included, what units or conventions are assumed, the chosen file format (or lack thereof), and quality of documentation. These factors together mean that close attention to detail is required to accurately combine disparate RV data sets while striving for high completeness. This is meticulous work that is very difficult to automate for a large sample of stars.

This was the main impetus for the SPORES-HWO RV Hunters Community Science Project, a roughly 3 month long citizen-science-style project whose aim was to compile as many public RV measurements as possible for the SPORES-HWO target stars, and to do so in an efficient,

consistent, and well-documented manner. Volunteers for SPORES RV Hunters were primarily undergraduate students at the University of California, Berkeley, whose primary majors were astrophysics or a related field. Through a combination of detailed written guidelines, online webinars, office hours, and digital collaboration, over 60 volunteers (see acknowledgments) were trained and assigned prioritized groups of target stars to investigate.⁷

To evenly distribute the workload, the 164 target stars were divided into 41 random target groups (each containing 4 target stars), and each volunteer was assigned to three target groups for a total of 12 target stars per person. The target groups were assigned in a particular order as to maximize redundancy, should any volunteer only complete a single group. If all volunteers completed all three of their assigned groups, then each target star would be investigated by at least four independent people, reducing the likelihood that any data were missed during the search.

Once the target groups were assigned, volunteers followed a general procedure to search for public RV data sets, organize the relevant columns, and submit their findings through an online portal. This process is shown graphically in Figure 4.2. The following resources were used to identify the RV data sets:

1. *LCES HIRES Archive*. The most recent data release from the Lick–Carnegie Exoplanet Survey Team (LCES) HIRES/Keck RV exoplanet survey⁸ (Butler et al. 2017) includes 75,062 RV measurements of 1700 stars through 2020 March 10. These data were measured at a spectral resolving power of $R \sim 60,000$ in the wavelength range 3700–8000 Å, using a gaseous iodine absorption cell located in the optical path for wavelength calibration (Butler and Marcy 1996). The LCES HIRES Archive was the default source for HIRES/Keck RVs in this work because of its high coverage of the northern hemisphere sky.
2. *HARPS RVBank Archive*. The HARPS RVBank⁹ is a public database of RVs from HARPS that have been corrected for systematic errors (Trifonov et al. 2020). The latest release of the HARPS RVBank contains more than 200,000 unique observations of over 5000 targets up to 2022 January (Perdelwitz et al. 2024). These data were measured with a spectral resolving power of $R \sim 115,000$ covering a wavelength range of approximately 3800–6900 Å, and a Th-Ar lamp with a dedicated fiber was used for wavelength calibration (Pepe et al. 2002). All RVs from the HARPS RVBank were rederived using the Spectrum Radial Velocity Analyser pipeline (Zechmeister et al. 2018, 2020). The HARPS RVBank was the default source for HARPS/ESO RVs in this work because of its extensive coverage of the southern hemisphere sky.
3. *California Legacy Survey*. The California Legacy Survey (CLS) catalog contains more than 100,000 RV measurements of 719 stars from three different spectrographs: HIRES/Keck, Levy/Automated Planet Finder (APF), and Hamilton/Lick. More information regarding

⁷All volunteers were required to agree to a code of conduct and expectations based on the AAS Code of Ethics (<https://aas.org/policies/ethics>) prior to receiving their target assignments.

⁸<https://ebps.carnegiescience.edu/data/hireskeck-data>

⁹https://www2.mpi-hd.mpg.de/homes/trifonov/HARPS_RVBank.html

these data can be found in R21. For any targets with HIRES/Keck data, we preferentially used the LCES archive instead of CLS when possible because of more recent updates to the LCES data.

4. *Lick Planet Search*. The 25 yr Lick Planet Search (LPS) contains more than 14,000 RVs for 386 stars that were observed between 1987 and 2011 with the Hamilton spectrograph at Lick Observatory. See Fischer et al. (2014) for more information. While the Hamilton/Lick RV data were already included in the CLS catalog for many stars, some target stars were only included in LPS.
5. *Laliotis et al. (2023)*. L23 examined archival RVs of potential targets for proposed DI missions in the southern hemisphere. They compiled RVs from HIRES/Keck, HARPS/ESO, Levy/APF, University College London Échelle Spectrograph (UCLES)/Anglo-Australian Telescope (AAT), and PFS/Magellan. See L23 for additional information. We collected HIRES/Keck, HARPS/ESO, and Levy/APF observations from this source only if they were not included in the previously listed sources. We note that most of the UCLES/AAT and PFS/Magellan data used for the present work were first published L23.
6. *ELODIE/SOPHIE Archives*. The OHP maintains archival spectra and RV measurements obtained from ELODIE¹⁰ and the Spectrographe pour l’Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes (SOPHIE)¹¹ (Moultaka et al. 2004). Although observations of some target stars are available on the ELODIE Archive, we chose not to include those data here due to the very large uncertainties derived from 1σ width of the CCF peak (on the order of a few kilometers per second). This did not appear to be an issue on the SOPHIE Archive, where the RV uncertainties were derived from either the CCF contrast and FWHM or the photon noise, depending on the signal-to-noise ratio of the observation. While we did obtain SOPHIE RVs for our target stars (selecting measurements flagged as “SCI”), we note that uncorrected instrumental drifts and nightly zero-point offsets were often present in the data, which complicated the analysis. We therefore excluded the SOPHIE RVs from the RV search and orbital fitting procedure in any systems where the instrumental effects were significant.
7. *Data & Analysis Center for Exoplanets*. The Data & Analysis Center for Exoplanets (DACE) RV archive¹² is a useful tool for identifying previously published RV data sets, especially those that are not part of large surveys or databases. We found additional RV data on DACE obtained from various spectrographs, including some that were not already found in the previously listed sources. In cases where RVs were available on DACE, we went back to the original source paper in order to download and document the data.

¹⁰<http://atlas.obs-hp.fr/elodie/>

¹¹<http://atlas.obs-hp.fr/sophie/>

¹²<https://dace.unige.ch/dashboard/>

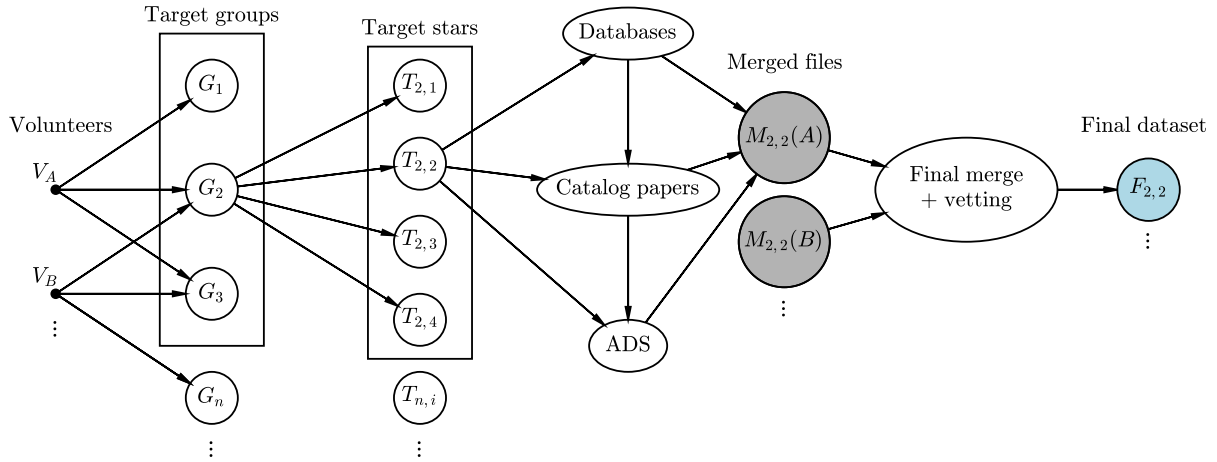


Figure 4.2: Flowchart summarizing the steps followed to compile the public RV data sets identified by the SPORES-HWO RV Hunters volunteers. The arrows in this example trace the data compilation progress for the second target star in target group 2 ($T_{2,2}$), from being assigned to volunteers to being completed as a final merged and vetted data set. Each volunteer is randomly assigned three target groups, with each target group containing four target stars from the SPORES-HWO Catalog. Multiple volunteers are assigned to the same target star for redundancy. The volunteers then collect and merge data from various databases, catalog papers, and ADS. Then, the merged data files from each volunteer are vetted and combined once more to create a final data set for each target star.

8. *Astrophysics Data Systems and VizieR.* Once the previous sources had been checked for RVs, we manually searched Astrophysics Data Systems (ADS)¹³ for individual articles or smaller catalogs with data for the target stars. These data were either downloaded from VizieR¹⁴ or accessed through the online journal.

Volunteers then merged the individual RV data sets for each of their targets into a single file with a standard predefined format. The individual data sets and merged file were then uploaded via an online portal for further processing. A total of over 1350 individual data sets and over 330 merged data files were submitted.

All 330 merged submissions were vetted semiautomatically for consistency and accuracy. The first step of the vetting process included checking that the proper units and column names were used, the telescopes were given consistent names, a reference was provided for each data point, null values were consistently formatted, there were no duplicates, and values were reasonable in both magnitude and sign. After making any appropriate corrections, we then manually cross-checked the multiple merged files for each target to check for completeness and correctness. We then took the union of the merged files to create a final vetted data set for each target. As an example, a subset of the final data set for the star HD 190360 is shown in Table 4.A3 in this chapter’s appendix.

¹³<https://ui.adsabs.harvard.edu>

¹⁴<https://vizier.cds.unistra.fr/viz-bin/VizieR>

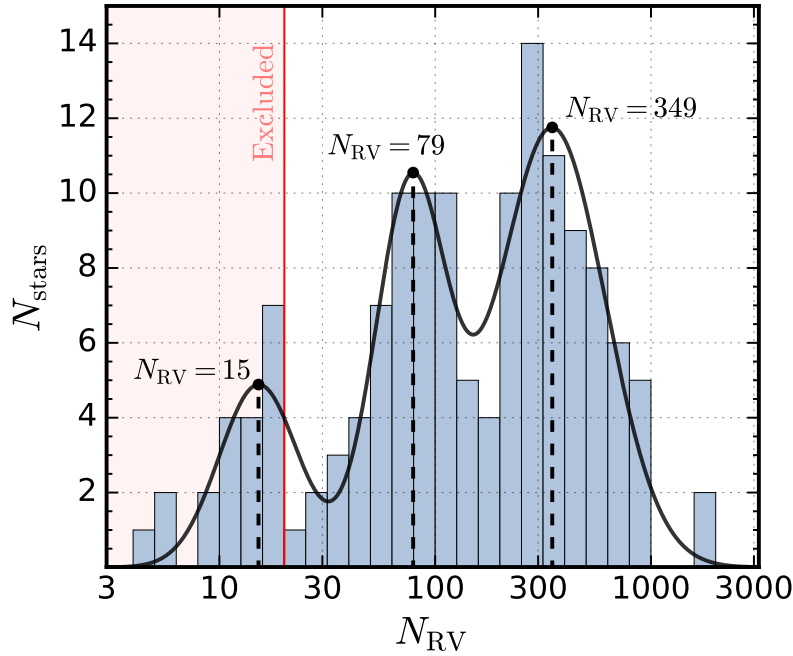


Figure 4.3: Histogram of the number of RV epochs obtained for each target star. Each histogram bin has a width of 0.1 dex. Interestingly, the stars appear to be clustered in roughly three groups based on how many times they have been observed, which we quantified using a best-fit three-Gaussian model (shown in black). The least-observed stars with fewer than 20 RVs were excluded from the analysis in this work. A 2D version of this histogram including the observational time span and the derived HZ sensitivity limits (Section 4.6) is shown in Figure 4.A3 in the appendix.

A histogram of the final number of RV epochs obtained for each target star is shown in Figure 4.3. In total, the SPORCS RV Hunters compiled 153,902 individual RV measurements of 141 stars, measured with 23 different spectrographs at 15 different observatories around the world over the last 36 yr. We note, however, that not all stars have been observed equally, as Figure 4.3 demonstrates. We found no public RV data for 23 stars, and fewer than 20 RVs were found for 21 stars. Interestingly, stars with more than 20 RV epochs appear to fall into roughly two categories: those with moderately good observational history (~ 80 RVs) and those with good or very good observational history (~ 350 RVs).

Stellar Activity Indicators

Inferring whether the gravitational effect of a planetary companion is responsible for periodic RV variations and avoiding false-positive detections require knowledge of any intrinsic variations of the host star. There are several well-known sources of SA that operate over a range of timescales and variability amplitudes. For example, acoustic oscillations in Sun-like stars, including p-mode oscillations, operate on timescales of several minutes and cause the stellar surface to pulsate with

an amplitude of the order of several meters per second (e.g., Gelly et al. 1986; Bouchy and Carrier 2001). Oscillations of a similar magnitude are also induced by surface granulation, or the rising and falling of convective cells of plasma, on timescales up to a day (e.g., Dumusque et al. 2011c; Meunier et al. 2015).

Of particular concern for this study are SA signals of Sun-like stars that can operate over timescales comparable to the orbital periods of potential planetary companions. In particular, magnetic activity-induced surface inhomogeneities such as starspots, plages, and faculae may be modulated by stellar rotation, leading to quasiperiodic oscillations in the observed RVs. These SA signals can have amplitudes at the $\sim 10 \text{ m s}^{-1}$ level for Sun-like stars with timescales on the order of the stellar rotation period (e.g., Donahue et al. 1997; Dumusque et al. 2011b; Haywood et al. 2016). Additional RV variations with periods comparable to the solar magnetic cycle ($\sim 11 \text{ yr}$) may also be driven by a star’s internal magnetic dynamos, with signal amplitudes exceeding $\sim 10 \text{ m s}^{-1}$ (e.g., Baliunas et al. 1996b; Dumusque et al. 2011a; Isaacson et al. 2024).

In order to vet any putative planet signals for false positives caused by SA, we therefore also collected several well-documented SA indicators during the search for RV measurements. One common SA indicator, the Mount Wilson S -index, is a measure of the relative flux in the Ca II H and K emission line cores at $3968 \text{ \AA}$ and $3934 \text{ \AA}$, respectively, compared to the local continuum flux (Wilson 1968; Duncan et al. 1991). The R'_{HK} is another common SA indicator based on the Ca II H and K lines, which is closely related to the S -index with corrections for bolometric flux and photospheric contribution (Middelkoop 1982; Hartmann et al. 1984; Noyes et al. 1984; Rutten 1984). The Ca II H and K lines are produced in active regions in the stellar chromosphere, where concentrated magnetic field lines are responsible for phenomena such as starspots. Therefore, time series observations of both the S -index and R'_{HK} are useful proxies for SA on the timescales of stellar rotation and stellar magnetic cycles.

Both S -index and R'_{HK} measurements were included for most stars with RVs in the LCES HIRES and HARPS RVBank archives. Other types of SA indicators were available for other data sets. When available, we also collected H -index or $H\alpha$ EW measurements, which both trace active regions in stellar chromospheres, in addition to the FWHM and BIS of the CCF, which both trace line profile variations caused by SA. Measurements of each of these SA indicators were submitted and vetted along with the SPORES RV Hunters data sets. In total, 43,649 epochs of SA indicator data were collected. These are summarized in Tables 4.1 and 4.A1 in the appendix.

4.4 Analysis

In this section, we describe the analysis of the RVs and SA indicator data. First, we describe the search for Keplerian signals in the RVs and how we quantify the RV search completeness. Then, we describe the analysis of periodic signals in the SA data and how we used those signals to vet false positives. The full figure sets from the analysis (e.g., Figures 4.4–4.6 and 4.A1–4.A2 in the appendix of this chapter) are available on Zenodo (see footnote 6).

Radial Velocity Search

We used the iterative RV search algorithm implemented in the open-source RVSearch package (R21) to identify periodic signals in the RV data and determine the best-fit Keplerian orbital solutions. Throughout the analysis, we binned the RVs to 0.5 day intervals to average over intranight stellar variability caused by p-mode oscillations. For each target star, the search begins with an initial model consisting of the RV data set and a likelihood function given by

$$\ln(\mathcal{L}) = \sum_i \left[\frac{(v_i - m(t_i) - \gamma_D)^2}{\sigma_i^2} + \ln(2\pi\sigma_i^2) \right], \quad (4.1)$$

where v_i is the i th RV measurement, σ_i^2 is the quadrature sum of the instrumental error and a jitter term, and γ_D is an instrumental velocity offset (R21). The RV model $m(t_i)$ at time t_i is given by

$$m(t) = \sum_n v(t|K_n, P_n, e_n, \omega_n, t_{c,n}) + \dot{\gamma}(t - t_0) + \ddot{\gamma}(t - t_0)^2, \quad (4.2)$$

where v is the n th Keplerian orbit signal at time t given RV semi-amplitude K , period P , eccentricity e , argument of periastron ω , and time of inferior conjunction t_c . Linear and quadratic trend terms are given by $\dot{\gamma}$ and $\ddot{\gamma}$, respectively, and t_0 is the median time of observation.

Our initial likelihood model contains a single-planet Keplerian model with uninformed orbital parameters. First, RVSearch determines the trend terms $\dot{\gamma}$ and $\ddot{\gamma}$ by fitting independent flat, linear, and quadratic models to the data, and then performing a statistical test to decide which trend model is preferred (R21). For this step, the Bayesian Information Criterion (BIC) is calculated for each trend model, defined as

$$\text{BIC} = -2\ln(\mathcal{L}) + k\ln(N), \quad (4.3)$$

where $\mathcal{L}$ is the likelihood of the given model, k is the number of free model parameters, and N is the total number of observations. A linear trend is preferred over a flat model if the difference in BIC between the models exceeds a threshold of $\Delta\text{BIC} = 5$. Likewise, a quadratic trend is favored over the linear model if the same ΔBIC threshold is exceeded.

Next, with the initial model in hand, RVSearch defines an orbital period search grid in which the spacing between adjacent frequency grid points is $\Delta f = \frac{1}{2\pi\tau}$, where τ is the observational baseline (R21). For each target, we define the limits of the period grid to be 3 and 10,000 days, unless the system contains a known planet with an orbital period shorter than 3 days. A goodness-of-fit periodogram is then constructed by stepping through the period grid and fitting a sinusoid at a fixed period to the data. The goodness of fit is quantified at each grid point by the ΔBIC between the best-fit model with $n+1$ planets and the model with n planets (i.e., a zero-planet model for the first iteration of the search).

The significance of each point in the ΔBIC periodogram is quantified by a false-alarm probability (FAP), which is determined empirically by extrapolating the log-scale histogram of periodogram power values (Howard and Fulton 2016; R21). We set an FAP threshold of 0.1% for any periodic signal to be considered significant. For any periodic signal that meets this criterion, RVSearch then refines the Keplerian model by performing a maximum a posteriori (MAP) fit with

all parameters free, and records the BIC of the best-fit model. At this stage, RVSearch implements Keplerian orbit fitting using the RadVel package (Fulton et al. 2018).

The algorithm proceeds by adding one additional planet to the RV model, conducting another grid search, and calculating a new ΔBIC periodogram by comparing the BIC of the $n + 1$ planet model to that of the best-fit n -planet model at each fixed period grid point. The empirical ΔBIC detection threshold corresponding to $\text{FAP} = 0.1\%$ is recomputed, and this process iterates until no further significant peaks are detected. The total number of parameters in the final model depends on both the number of planets detected and the number of instruments used to observe the system. For example, the model for a system with two planets observed by four instruments would include up to 20 parameters: 12 parameters shared across instruments (two sets of five Keplerian orbit components plus two, one, or zero trend terms) and 8 parameters unique to each instrument (four sets of instrumental offset and jitter terms).

Once the search process is complete and the MAP estimates of the final model parameters are calculated, RVSearch samples the posteriors using an affine-invariant Markov Chain Monte Carlo (MCMC) implemented in *emcee* (Foreman-Mackey et al. 2013) and RadVel (Fulton et al. 2018). We sample the posteriors in the default RadVel basis $\{\log P, K, \sqrt{e} \sin \omega, \sqrt{e} \cos \omega, t_c\}$ assuming uniform priors on all parameters.¹⁵ For a comprehensive review of RadVel’s MCMC implementation, see Fulton et al. (2018).

Finally, we derive P , e , and ω from the converged posteriors using the standard utility functions provided in RadVel. Using the stellar masses and uncertainties adopted from the SPORRES-HWO Catalog (Harada et al. 2024), we also derive the semimajor axis a using Kepler’s third law, and the projected planet mass according to

$$\frac{M_p \sin i}{M_{\text{Jup}}} = \frac{K \sqrt{1 - e^2}}{28.4 \text{ m s}^{-1}} \left(\frac{M_\star + M_p}{M_\odot} \right)^{2/3} \left(\frac{P}{\text{yr}} \right)^{1/3}, \quad (4.4)$$

where $M_\star$ is the stellar mass.

Each unique Keplerian signal identified by RVSearch is listed in Table 4.A4 in this chapter’s appendix. Any signals associated with known planets or companions are listed with the corresponding planet letter and classified as “known companion” (KC). Otherwise, each signal has been assigned an arbitrary decimal ID number in the order it was detected. For each signal, Table 4.A4 provides the posterior median and 1σ uncertainty values for P , T_c , e , ω , K , $M_p \sin i$, and a , alongside the FAP associated with the detection and a classification of the signal. For systems where we detected a linear or quadratic, we list the posterior median and 1σ uncertainty values for $\dot{\gamma}$ and $\ddot{\gamma}$ in Table 4.A5 in the appendix.

An example RVSearch summary plot for the HD 190360 system is shown in Figure 4.4, which includes the full RV time series and best-fit model, ΔBIC periodograms, and phase-folded orbit plots (the converged posterior distributions of the MCMC fit parameters and derived planet parameters are shown in Figures 4.A1 and 4.A2 this chapter’s appendix). HD 190360 has at least two known planets, an inner Neptune-mass planet and an outer Jovian planet (e.g., Naef et al. 2003;

¹⁵We enforce two hard bounds constraining $K > 0$ and $0 \leq e < 1$ (R21).

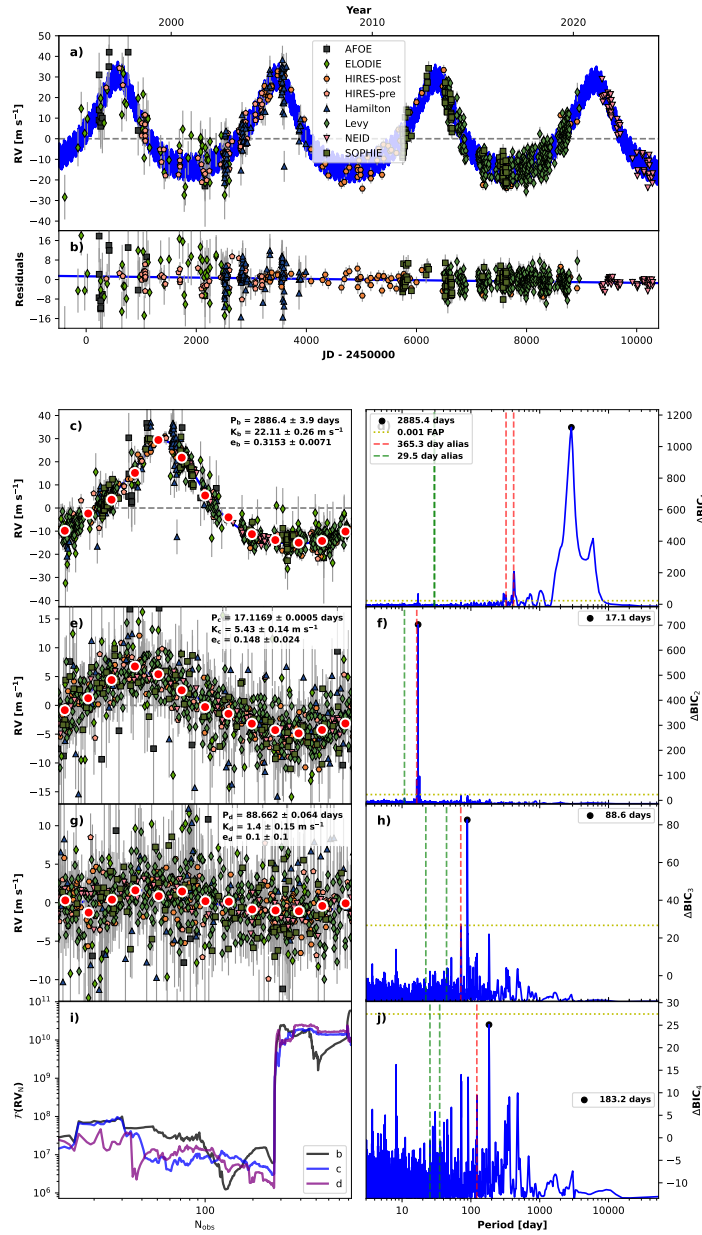


Figure 4.4: Example RVSearch summary plot for HD 190360, a bright ($V = 5.7$) G7IV-V star orbited by at least two known planets and one additional planet candidate. Panel (a) shows the full RV time series with the best-fit total model overplotted in blue, while panel (b) shows the residuals to the best-fit three-planet Keplerian model. Panels (c), (e), and (g) show the phase-folded RVs associated with the ΔBIC periodograms in panels (d), (f), and (h). Panel (i) shows the running Lomb–Scargle periodograms for each signal, and panel (j) shows the ΔBIC periodogram of the final residuals.

(The full set of 120 summary plots can be accessed online in Harada et al. (2025) at the publisher’s website.)

Vogt et al. 2005), which were easily detected by RVSearch. We also detect a third PC in this system, a sub-Neptune-mass planet on an 88.66 day orbit, which we discuss more in Section 4.5.

We note that RVSearch sometimes identifies RV signals with periods greater than or comparable to the observational baseline. In these cases, the MCMC may converge to a nonphysical period that is much greater than the one corresponding to the periodogram peak. In such cases, the uncertainties in the posterior median period and amplitude may be overly inflated due to poor sampling. Following L23, we label these detections as long-period signals (LPS) and record only the period corresponding to the peak of the ΔBIC periodogram (Table 4.A4 in the appendix).

Injection and Recovery Tests

A key goal of this study is to determine limits on undetected planets in each of the target systems given the existing public RV data. We empirically measure the search completeness for each system with at least 20 RV epochs as a function of semimajor axis and $M_p \sin i$ using Keplerian injection and recovery tests. We used the injection and recovery functionality implemented in the RVSearch package (R21).

We inject 10,000 individual synthetic Keplerian signals into the residuals from the best-fit RV model described in the previous subsection. The periods and RV amplitudes of the synthetic planets are drawn from log-uniform distributions spanning from 3 to 10^6 days and 0.1 to 1000 m s^{-1} , respectively. For simplicity, we assume all orbits are circular. The search algorithm then attempts to recover each synthetic planet. The result is a map in semimajor axis versus $M_p \sin i$ space showing which hypothetical planets would or would not be detectable.

The results of the injection and recovery tests are then used to compute the search completeness for each data set, shown as contours of the detection probability in the a versus $M_p \sin i$ plane. Figure 4.5 shows an example of the injection and recovery results for HD 190360 with the corresponding completeness contours. For this system, which has a total of 835 RV epochs from eight different instruments spanning 29.2 yr, we find that a hypothetical $M_p \sin i \approx 15 M_\oplus$ planet would have a detection probability of about 50% at an orbital separation of 1 au. Therefore, a Neptune-mass or more massive planet at this semimajor axis should be detectable, while any lower-mass planets would remain undetectable given the available RV data. As expected, the detection sensitivity begins to drop off steeply at orbital separations $\gtrsim 10$ au due to the limited temporal baseline of the RV observations. RVSearch completeness plots for all systems with at least 20 epochs of data are available.

Stellar Activity Analysis

In order to help us identify potential SA signals and vet any new RV signals for false positives, we compute the generalized Lomb–Scargle (GLS) periodogram (Zechmeister and Kürster 2009) of any available SA indicators. Proceeding from the RV search procedure, we compute up to six sets of SA GLS periodograms for each target: S -index, H -index, $\text{EW}_{\text{H}\alpha}$, R'_{HK} , BIS, and FWHM. For comparison, we also compute GLS periodograms for the RVs and the observational window function.

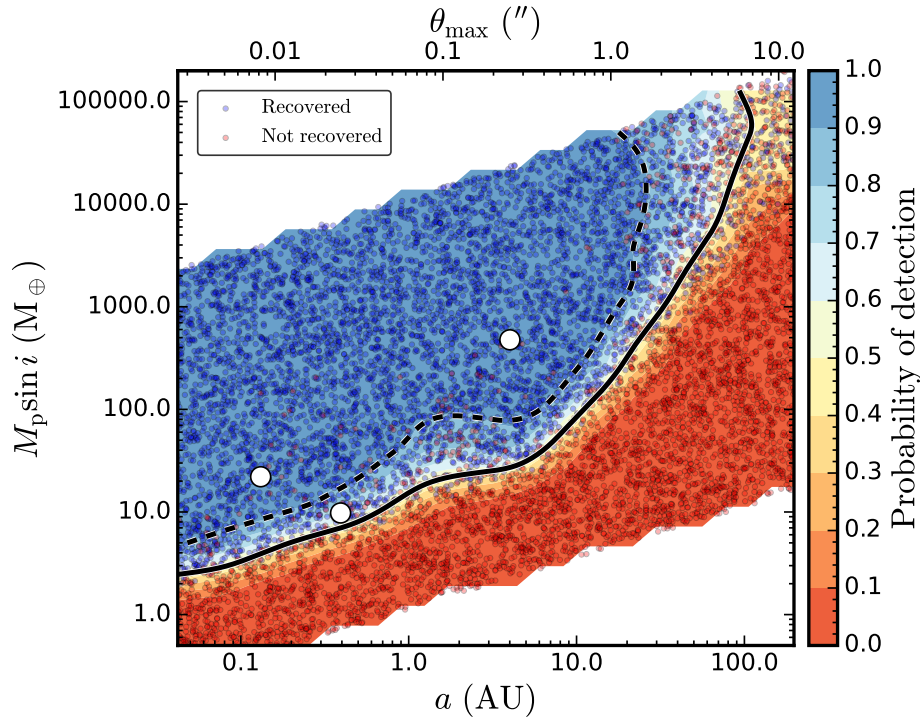


Figure 4.5: Example RVSearch completeness plot for HD 190360 computed from the RV residuals shown in Figure 4.4. Each point represents a simulated Keplerian (circular) orbit in the $M_p \sin i$ vs. a plane, where the blue points have been recovered by RVSearch, and the red points have not. The top axis shows the converted maximum angular separation of the orbit given a and the star’s parallax. Detection probability contours are shown by the color scale. The 50% completeness contour is indicated by the solid black line, and the 90% contour is shown by the dashed black line. The three Keplerian signals recovered by RVSearch are shown as white circles.

(The full set of 120 completeness plots can be accessed online in Harada et al. (2025) at the publisher’s website.)

For each SA indicator, we first compute GLS periodograms one instrument at a time for any instruments with at least 10 measurements. We iteratively remove 5σ outliers and bin the SA measurements to nightly intervals before calculating each periodogram using the Lomb–Scargle autopower function implemented in *astropy* (Astropy Collaboration et al. 2013, 2018). Computing instrument-by-instrument periodograms allows us to isolate any potential instrumental systematics that could introduce false-positive RV signals. After removing any instrumental offsets, we then stitch together the SA data to compute the combined GLS periodogram. This process is also repeated for the RVs and the window function.

We then generate a set of diagnostic plots for each target comparing any signals detected by RVSearch with the SA GLS periodograms. For each activity indicator, the diagnostic plot shows the combined and instrument-by-instrument periodograms for both the RVs and the SA data. Any

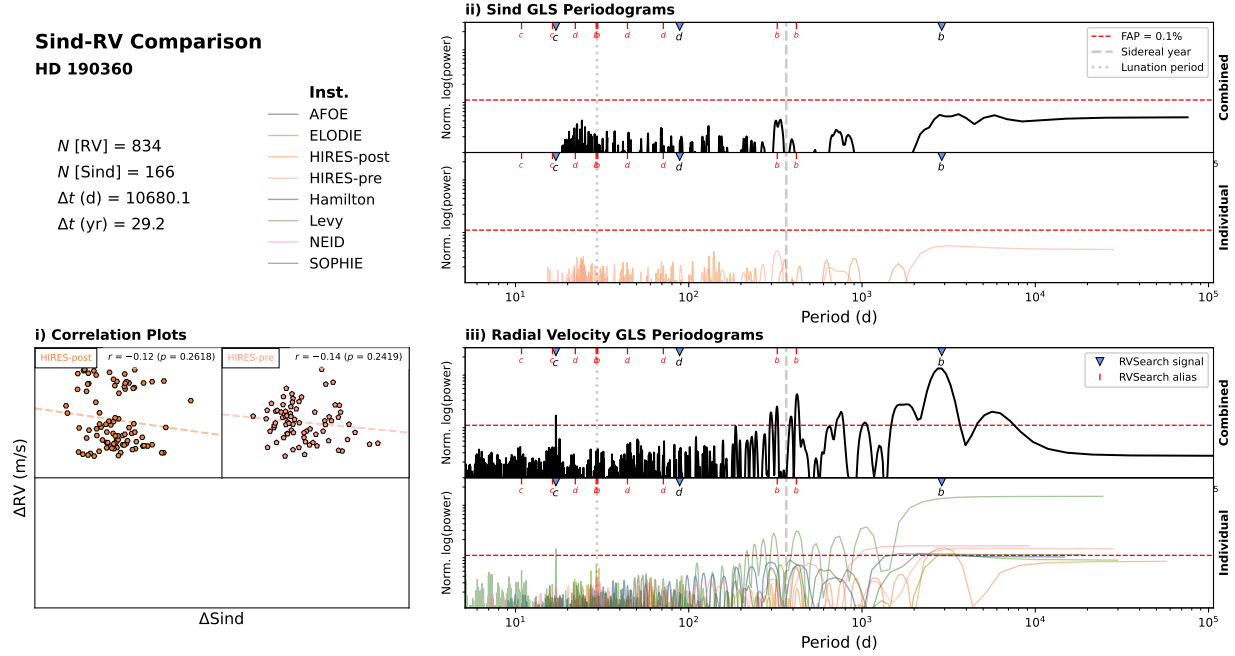


Figure 4.6: Example stellar activity diagnostic plot for the S -index measurements of HD 190360. Panel (i) shows the correlation between the RVs and S -index values (by instrument). The Pearson correlation coefficient and its corresponding p -value are shown in the inset. Panel (ii) shows the generalized Lomb–Scargle (GLS) periodogram (Zechmeister and Kürster 2009) of the S -index measurements for the combined data set (top) and individual instruments (bottom). The 0.1% FAP level is indicated by the red dashed line. Keplerian RV signals identified by RVSearch are indicated by the blue triangles, and their alias periods with the sidereal year and the lunation period are indicated by vertical red ticks. Panel (iii) is the same, but for the RV measurements.

(The full set of 567 stellar activity diagnostic plots can be accessed online in Harada et al. (2025) at the publisher’s website.)

RVSearch signals and their yearly and lunation period aliases are overplotted for comparison. The diagnostic plots also show instrument-by-instrument scatter plots of the SA indicator versus RV and the corresponding Pearson correlation coefficient and p -value. An example diagnostic plot for the S -index data for HD 190360 is shown in Figure 4.6. For this system, the S -index diagnostic plot shows no evidence that any of the RVSearch signals are false alarms (FAs) or false positives due to SA. All diagnostic plots for the systems analyzed here are available for download.

All of the diagnostic plots are then used to help classify any RV signals detected by RVSearch as either FA, SA, PC, or source requiring confirmation (SRC). Alternatively, signals may be classified as a KC or a poorly constrained long-period signal (LPS), as described earlier in this section. The classifications are described on a case-by-case basis in Section 4.5 and in Appendices 4.B, 4.C, and 4.D at the end of this chapter.

4.5 Results

Here, we present the main results of the RV analysis. We start by summarizing the potential Keplerian signals identified by RVSearch, highlighting six systems with novel detections. We then summarize the search completeness of all the stars in the sample.

RV Search Results

We analyzed 120 of the 164 provisional HWO target stars identified in the EMSL and SPORES-HWO Catalog (Mamajek and Stapelfeldt 2024; Harada et al. 2024) for which we had at least 20 epochs of RV observations. While we also compiled public RV data for 21 additional target stars, these stars were excluded from the analysis because they had fewer than 20 nights of observations. For the 120 target stars we analyzed, we used RVSearch (R21) to find a total of 109 potential Keplerian signals in 49 unique systems (Table 4.A4 in the appendix), which could be produced by either gravitationally bound companions (stellar or planetary), SA (magnetic cycles or rotationally modulated surface inhomogeneities), or instrumental systematics or aliases.

Of the 120 systems, we found that 74 also show evidence of a long-term trend in the RVs (Table 4.A5 in the appendix), which could be fit by either a first-order or a second-order polynomial. Many of these trends are associated with known stellar companions on wide orbits,¹⁶ while others are likely produced by distant planetary companions or SA cycles with periods longer than the observational baseline.

Of the 164 target stars, we note that 30 have at least one previous claim of a planet detection (see footnote 1), totaling up to 70 known planets in the whole sample. We recovered 51 known planetary signals, whose updated orbital parameters are shown in Table 4.A4 and discussed in Appendix 4.B. For the other 19 known planets, we summarize their nondetections in Table 4.A6 and in Appendix 4.C. We found that these undetected planets were often either disputed as PCs in the literature or required additional observations such as astrometry or imaging to be detected. In other cases, the planetary signal simply did not reach the statistical significance required to be considered detections in this work, or the discovery RV data simply were not publicly available.

We identified two additional signals originating from known stellar binaries, in cases where approximately one full orbit of the stellar companion was measured: HD 165499 and HD 212330 A (see Appendix 4.B). We caution that HD 165499 is not currently listed in the Washington Double Star Catalog¹⁷ (WDS; Mason et al. 2001), and therefore, there is no indication in the EMSL that this star has a stellar companion. More alarmingly, HD 212330 A is shown as a binary in the EMSL, but the reported WDS angular separation ($23''.6$) is much larger than the maximum angular separation of the companion measured in the RV data at $\sim 16,000$ days. The companion properties shown in the EMSL could correspond to a wider-separation stellar companion, given that we ob-

¹⁶We note that, for stars with imaging and/or astrometry observations, it may be possible to use nondetections and sensitivity limits from those measurements to place limits on the luminosities and separations of stellar companions that might be responsible for the observed RV trends. While this is beyond the scope of the present analysis, we will investigate these observations in future work.

¹⁷<https://www.astro.gsu.edu/wds/>

Class	Definition	Count
KC	Known Companion	51
KC-S	Known Companion, Stellar	2
SA	Stellar Activity	17
SA-R	Stellar Activity, Rotation	9
LPS	Long-period Signal	5
FA	False Alarm	19
PC	Planet Candidate	4
SRC	Source Requiring Confirmation	2
Total		109

Table 4.2: Summary of RV Signal Classifications.

serve a long-term trend in the CORALIE RVs, but it is also possible that the information is simply inaccurate or out of date. Both of these stars are ranked in Tier B of the EMSL. However, Mamajek and Stapelfeldt (2024) intended to exclude binaries with stellar companions separated by less than $3''$. Based on this criterion, HD 165499 and HD 212330 A should not have made the cut for the EMSL to begin. This raises concerns about the reliability of the WDS catalog for exoplanet DI target lists, considering that close stellar companions could pose a major challenge for coronagraphic starlight suppression.

We classified each of the remaining 56 RV signals based on the SA diagnostic plots (e.g., Figure 4.6) and previous results from the literature. We determined that 26 signals were caused by SA in the form of either magnetic activity cycles or rotationally modulated activity (SA or rotational stellar activity, hereafter SA-R). Another 19 of the signals were classified as FA due to instrumental systematics or aliasing, and 5 signals were classified as long-period signal (LPS) as defined in Section 4.4. The last six signals were classified as either PC or sources requiring classification (SRC). These signals were not obviously associated with any known planets, SA, instrumental effects, or aliases. Following L23, we classified a signal as PC if the periodogram peak was well defined and the RV signal strength increased roughly monotonically with the number of RV observations. In more ambiguous cases (e.g., multiple periodogram peaks clustered around a narrow range of periods), we labeled the signal as SRC, indicating that more data or more sophisticated modeling is needed to robustly classify the signal. We classified four RV signals as PC and two RV signals as SRC.

All of the signal classifications are summarized in Table 4.2. We elaborate on these classifications in six systems with newly detected signals (PC or SRC) in the following subsections. More detailed discussion of the classifications in systems with updated parameters of known planets can be found in Appendix 4.B, and discussion of nondetections in systems with previously reported planet can be found in Appendix 4.C. Lastly, all other noncompanion classifications are discussed in Appendix 4.D.

HD 190360

HD 190360 (HIP 98767; HR 7670; GJ 777 A; TIC 105999792) is a G7IV-V star (Gray et al. 2006) at a distance of $d = 16.003 \pm 0.009$ pc (Gaia Collaboration 2022a). This system hosts an eccentric Jovian planet and an inner Neptune planet, which were first detected with RV observations from ELODIE/OHP, Advanced Fiber-Optic Échelle spectrometer (AFOE)/Whipple, and HIRES/Keck (Naef et al. 2003; Vogt et al. 2005). The properties of these two planets have since been revised by further ground-based RVs (Wright et al. 2009; Courcol et al. 2015; R21) and astrometry from Gaia and Hipparcos (Feng et al. 2021). In this work, we detected both previously known planets orbiting HD 190360 using 835 public RVs from the AFOE/Whipple, ELODIE/OHP, HIRES/Keck, Hamilton/Shane, Levy/APF, NEID/WIYN, and SOPHIE/OHP spectrographs, improving the precision on both period and semiamplitude by at least a factor of 2 compared to previous literature values (see Table 4.A4 in the appendix; and Wright et al. 2009; Feng et al. 2021). We also find evidence of a linear trend in the RVs (Table 4.A5 in the appendix), which is likely produced by HD 190360’s faint stellar companion.

In addition to the two previously-confirmed planets, we also detected a third planet candidate, HD 190360 d ($P_d = 88.662^{+0.065}_{-0.064}$ days, $M_d \sin i = 10.0 \pm 1.0 M_\oplus$), as shown in Figure 4.4. This signal was first identified as a planet candidate in an analysis by Hirsch et al. (2021). Interestingly, R21 also found a signal at 90.34 days which they classified as a false-positive, likely due to how close the period is to the 1/4 annual harmonic. More recently, Giovinazzi et al. (2025a) found a similar periodicity at 90 days using newer RV data from NEID. The period we recovered is not consistent with the 1/4 annual harmonic and is not obviously associated with any SA signals; hence, we classified it as a PC. During the revision stage of this paper, the confirmation of HD 190360 d was announced by Giovinazzi et al. (2025b), who conducted a more thorough investigation of the system using both RVs and astrometry from Gaia and Hipparcos. Our results for HD 190360 d are consistent with their orbital solution, but with slightly higher uncertainties.

HD 192310

HD 192310 (HIP 99825; HR 7722; GJ 785; TIC 326096771) is a K2+V star (Gray et al. 2006) at a distance of $d = 8.812 \pm 0.004$ pc (Gaia Collaboration 2022a). This system hosts two known planets with orbital periods of about 74 and 526 days (Howard et al. 2011; Pepe et al. 2011). Using 768 RVs from HARPS/ESO, HIRES/Keck, PFS/Magellan, and UCLES/AAT, we detected both known planets at periods of $P_b = 74.262 \pm 0.032$ days and $P_c = 546.5 \pm 3.4$ days, consistent with recent results for this system (L23).

We also identified four additional signals not associated with any known planets in this system (Table 4.A4 in the appendix). Two of the signals at periods of $P = 43.623^{+0.025}_{-0.024}$ day and $P = 39.44^{+0.05}_{-0.03}$ d have been attributed to differential stellar rotation (L23, Lovis et al. 2011), and another signal at $P = 5650.0^{+4000.0}_{-1600.0}$ days is consistent with a previously reported SA cycle (Lovis et al. 2011). The sixth signal we detected at $P = 24.567^{+0.02}_{-0.018}$ days does not match with any known planets or SA. The signal has an amplitude of $K = 0.632 \pm 0.1 \text{ m s}^{-1}$, corresponding to a planet mass of $M_p \sin i = 2.3^{+0.38}_{-0.37} M_\oplus$. L23 also reported a significant signal with the same periodicity

and noted a well-defined periodogram peak and well-constrained posteriors. We found very similar results for this system using the same data but with an additional 10 nights of HIRES/Keck data. Following L23, we classified this signal as a PC. Finally, we note that the best-fit model for this system prefers a quadratic trend term (Table 4.A5 in the appendix), which may hint at a long-period companion or SA signal.

HD 210302 (τ PsA)

HD 210302 (τ PsA; HIP 109422; HR 8447; GJ 9770; TIC 97402436) is an F6V star (Gray et al. 2006) at a distance of $d = 18.46 \pm 0.03$ pc (Gaia Collaboration 2022a) with no KCs. Analyzing 35 RVs from HIRES/Keck and 43 RVs from HARPS/ESO, we detected a single periodic signal at $P = 115.52^{+0.19}_{-0.27}$ days with an amplitude of $K = 8.3^{+1.6}_{-1.4}$ m s⁻¹. This signal was only weakly detected with an FAP of 0.046%, and we note a high level of scatter in the residuals and incomplete orbital phase coverage. A small peak in the GLS periodogram of R'_{HK} measurements from HARPS/ESO and a correlation between R'_{HK} and the RVs (Pearson correlation $r = 0.65$ with $p \ll 0.05$) suggest that this signal may be associated with SA. However, we currently do not have enough data to confirm whether the R'_{HK} periodicity is statistically significant and rule out the possibility that the signal is planetary in nature. We therefore classify the signal as SRC until further observations can be obtained.

HD 217987 (Lacaille 9352)

HD 217987 (Lacaille 9352; HIP 114046; GJ 887; TIC 155315739) is an M1.0V star (Dieterich et al. 2012) at a distance of $d = 3.2871 \pm 0.0005$ pc (Gaia Collaboration et al. 2018). This system was recently reported to have two super-Earths and a possible third planet in a comprehensive study of RVs from HARPS/ESO, HIRES/Keck, PFS/Magellan, UCLES/AAT, and photometry from TESS (Jeffers et al. 2020). Using the publicly-available HARPS/ESO and HIRES/Keck data, we found consistent orbits for the two known planets, GJ 887 b and GJ 887 c, with periods of $P_b = 9.26177^{+0.00055}_{-0.00053}$ days and $P_c = 21.7952^{+0.0025}_{-0.0024}$ days. However, we did not detect the putative ~ 50 day signal identified by Jeffers et al. (2020), instead finding a potential new signal at $P = 39.223^{+0.016}_{-0.015}$ days with an amplitude of $K = 2.28^{+0.34}_{-0.32}$ m s⁻¹. Jeffers et al. (2020) noted that GJ 887 is an unusually quiet M dwarf, and therefore were unable to determine a rotation period for the star based on its TESS light curve. Without knowing the stellar rotation period, we cannot confidently classify the 39 day signal detected here as either SA or planetary in nature. Therefore, we report this signal as SRC.

HD 219134

HD 219134 (HIP 114622; HR 8832; GJ 892; TIC 283722336) is a K3V star (Keenan and McNeil 1989) at a distance of $d = 6.542 \pm 0.002$ pc (Gaia Collaboration 2022a). This star hosts a multiplanet system with at least five known planets with masses ranging from $M_p \sin i = 4.36 M_\oplus$ to $108 M_\oplus$ and with orbital periods ranging from about 3 days to 6 yr (Vogt et al. 2015). At least two of the planets, HD 219134 b and HD 219134 c, have been detected in transit by TESS

and Spitzer (Motalebi et al. 2015; Gillon et al. 2017a; Seager et al. 2021). In this work, we detected five known planets (b, c, d, f, and h) using 543 RVs from High Accuracy Radial Velocity Planet Searcher for the Northern Hemisphere (HARPS-North)/Telescopio Nazionale Galileo (TNG), HIRES/Keck, Hamilton/Shane, and Levy/APF (Table 4.A4 in the appendix). Our derived planet properties and orbits are consistent with previously published results with improvements in the orbital period precision of up to a factor of 3 (Vogt et al. 2015; Gillon et al. 2017a).

In addition to the five known planets, we also detected a long-period signal (LPS) with a periodogram peak at 19,241.3 days (~ 52 yr) and the star’s rotation period at $P = 43.475^{+0.024}_{-0.026}$ days (Motalebi et al. 2015). Notably, we did not detect the putative planet g at 94.2 days that was published in the original study (Vogt et al. 2015). In fact, there have been no subsequent detections of planet g in the literature, despite independent analyses of the system by multiple authors (Gillon et al. 2017a; Rosenthal et al. 2022). We therefore consider planet g to be a disputed planet detection. However, we did detect one additional signal in this system with a period of $P = 192.32^{+0.45}_{-0.39}$ days and an amplitude of $K = 2.03 \pm 0.17 \text{ m s}^{-1}$ (which we refer to as HD 219134.04). Interestingly, Rosenthal et al. (2022) also recovered this 192 day signal and reported it as a systematic, while Hirsch et al. (2021) suggested that it may be the actual period of planet g (as 94 days is close to the 1/2 harmonic of the signal). We classified HD 219134.04 as PC, but note that a closer investigation of the data for this system is needed to robustly determine its origin. Finally, we also find evidence of a long-term quadratic trend in the RVs (see Table 4.A5), which is likely associated with the orbit of HD 219134’s faint stellar companion.

HD 219623

HD 219623 (HIP 114924; HR 8853; GJ 4324; TIC 24467943) is an F8V star (Gray et al. 2001) with no known planets at a distance of $d = 20.61 \pm 0.02 \text{ pc}$ (Gaia Collaboration 2022a). Measurements from Spitzer show that this star has an infrared excess ($\geq 3\sigma$ at $70 \mu\text{m}$), suggesting the presence of a debris disk (Beichman et al. 2006). Our analysis of 36 RVs from HIRES/Keck spanning 11.5 yr revealed a significant signal (FAP = 0.02%) at $P = 48.481^{+0.046}_{-0.038}$ days with an amplitude of $K = 9.4 \pm 1.3 \text{ m s}^{-1}$, corresponding to planet mass of $M_p \sin i = 49.3^{+7.5}_{-7.3} M_{\oplus}$.

We found that the peak in the ΔBIC periodogram was well defined, and the strength of the signal increased roughly monotonically with the number of observations. We also note that HD 219623 is a relatively inactive star with $R'_{\text{HK}} = -4.993$ (Isaacson and Fischer 2010), ranking in the 16th percentile of all R'_{HK} values in the sample. There were no significant peaks in the SA periodograms, and there were no significant correlations between the RVs and SA indicators. Additionally, HD 219623’s measured rotation of $v \sin i = 5.50 \text{ km s}^{-1}$ (Mishenina et al. 2012), combined with its radius of $1.29 R_{\odot}$ (Harada et al. 2024), corresponds to a maximum rotation period of about 11.9 days. HD 219623 is also an earlier spectral type than the Sun and is near the lower end of the Kraft break (Kraft 1967) with an effective temperature of $T_{\text{eff}} = 6080 \pm 43 \text{ K}$ (Harada et al. 2024), so we would not expect this star to rotate slowly. Therefore, the 48 day RV signal is unlikely associated with stellar rotation. Provided these factors, we cannot rule out a planetary origin for the 48 day signal given the 36 available RVs, and hence classify this signal as a PC requiring additional data and analysis.

Search Completeness

We quantified the RV search completeness for each target star with at least 20 RV epochs by running injection and recovery simulations as described in Section 4.4. Search completeness varies significantly between different targets and can depend strongly on stellar spectral type, instrument precision and systematics, number of observations, survey cadence and baseline, and gaps between observations. Therefore, to assess and compare the achieved search completeness between different targets across the sample, we computed the value of $M_p \sin i$ as a function of a at which 50% of injected planet signals are recovered for a given system. To achieve this, we fit a cubic B-spline smoothing function with the regularization parameter $\lambda = 1$ to the contour of 50% detection probability from the completeness plot of each system (e.g., Figure 4.5). Hereafter, we will refer to this as the “50% completeness level” (CL₅₀).

Figure 4.7 shows all 120 CL₅₀ lines for targets with ≥ 20 epochs of data. Using the stellar parallaxes compiled in the EMSL and SPORES-HWO Catalog (Mamajek and Stapelfeldt 2024; Harada et al. 2024), we also calculated the CL₅₀ values as a function of maximum angular separation $\theta_{\max}$ assuming circular orbits. We converted the semimajor axis to $\theta_{\max}$ using $\theta_{\max} = \varpi(a/\text{au})$, where ϖ is the stellar parallax in arcseconds. To assess the search completeness in relation to the conservative and optimistic HZ limits (Kasting et al. 1993; Kopparapu et al. 2013), we then also calculated the CL₅₀ values as a function of instellation flux using $S/S_{\oplus} = (L_{\star}/L_{\odot})(a/\text{au})^{-2}$, where $L_{\star}$ is the stellar luminosity from the SPORES-HWO Catalog. Figure 4.7 shows the CL₅₀ of each star in terms of $M_p \sin i$ and K as a function of a , $\theta_{\max}$, and S .

The CL₅₀ lines in Figure 4.7 follow the general expected behavior from analytic arguments: the minimum detectable mass increases roughly as $M_p \sin i \propto a^{1/2}$ (see Equation (4.4)) for $a \lesssim (M_{\star}/M_{\odot})^{1/3}(t_{\text{span}}/\text{yr})^{2/3}$ au, where t_{span} is the temporal baseline of the RV observations. At larger values of a , the minimum detectable mass increases steeply as we rapidly lose sensitivity to planets whose orbital periods are $\gtrsim t_{\text{span}}$. Deviations from this behavior on a system-by-system basis result from differences in stellar spectral type, instrument characteristics, survey cadence and baseline, and gaps between observations.

For a typical star in the sample (i.e., the median CL₅₀; solid orange line in Figure 4.7), we could expect to detect planets with masses¹⁸ as small as about $10 M_{\oplus}$ at a distance of about $a = 0.05$ au with at least 50% probability. The minimum detectable planet mass increases to approximately $50 M_{\oplus}$ at $a = 1$ au, and to $200 M_{\oplus}$ at $a = 5$ au. At farther orbital distances, the typical minimum detectable planet mass increases more rapidly, with no planets less massive than $\sim 5 M_J$ detectable at $a \gtrsim 10$ au for the median CL₅₀.

At a fixed semimajor axis of $a = 0.1$ au, the middle 68% of CL₅₀ lines have $M_p \sin i$ limits between about $5 M_{\oplus}$ and $80 M_{\oplus}$ (dashed orange lines in Figure 4.7). At $a = 0.3$ au, the middle 68% of CL₅₀ lines are between about $8 M_{\oplus}$ and $150 M_{\oplus}$, and at $a = 1$ au, the middle 68% of lines are between about 1 Neptune-mass ($17 M_{\oplus}$) and about 1 Jupiter-mass ($318 M_{\oplus}$). In the worst case

¹⁸Throughout this discussion, we sometimes use “planet mass” and $M_p \sin i$ interchangeably, despite these being different quantities. Unless otherwise specified, “planet mass” here will actually refer to $M_p \sin i$. The completeness maps were calculated in K -space, but of course, we gain the $\sin i$ degeneracy factor when we convert K to a mass using Equation (4.4).

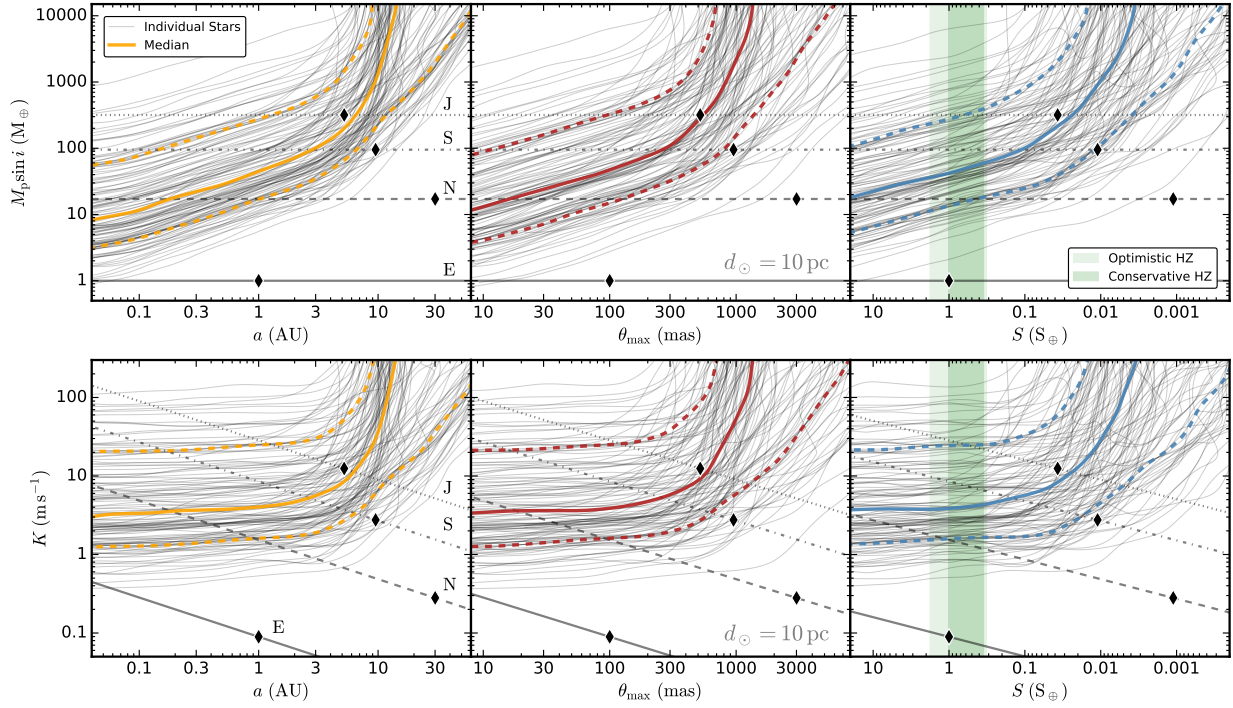


Figure 4.7: Contours of 50% search completeness (CL_{50}) for the 120 stars with at least 20 nights of RVs (black lines). Top: from left to right, each panel shows the same CL_{50} lines as a function of $M_p \sin i$ and semimajor axis, maximum projected separation (assuming circular orbits), and stellar insolation flux. The median CL_{50} in each panel is shown by the solid colored line in either orange, red, or blue. The middle 68% of CL_{50} lines are between the dashed colored lines. The conservative and optimistic HZs for a solar twin (Kasting et al. 1993; Kopparapu et al. 2013) are indicated by the green shaded regions in the rightmost panel. Bottom: same as the top row, only with RV semiamplitude K shown on the vertical axis. Earth, Neptune, Saturn, and Jupiter values are indicated by black diamonds in each panel, assuming $e = 0$, $i = 90^\circ$, and $d = 10$ pc for a solar twin.

(for the stars with at least 20 RVs), we could not expect to detect any planets less massive than a few M_J . On the other hand, in the best-case scenario, a $\sim 1 M_\oplus$ planet could be detected within $a \leq 0.05$ au (assuming stellar effects do not limit planet sensitivity at this level), and a $\sim 6 M_\oplus$ planet could be detectable at $a = 1$ au. Further discussion of the search completeness results and implications can be found in Section 4.6.

4.6 Discussion

In this section, we discuss the results from our analysis of archival RVs. First, we discuss the context of these results in relation to past studies of Doppler sensitivity to planets around nearby stars. We then take a closer look at planet sensitivity limits in the HZs of the target stars and the

stars that currently lack sufficient RV observations. Lastly, we discuss what we currently know or do not know about the architectures of these nearby planetary systems and how this may inform future precursor science studies for the HWO exoEarth survey.

Comparison to Past Work

This study showcases the planet-detecting capability of over 35 yr of precision RV monitoring. Compared to past research analyzing Doppler constraints on planetary companions to nearby stars, this work shows an overall improvement in RV search sensitivity thanks to a broader scope of global, multidecade RV monitoring efforts (Howard and Fulton 2016, L23). In this work, we have studied a larger, more complete sample of 120 nearby stars that are likely to be observed by a future high-contrast imaging mission like HWO. We have also included data from significantly more instruments by compiling over 150,000 RV measurements that were publicly available from a wide variety of resources.

For example, Howard and Fulton (2016) previously analyzed a sample of 76 stars with RVs from HIRES/Keck and the Hamilton/Shane, which were observed by the California Planet Survey between 1987 and 2014. They selected stars with spectral types no earlier than F8 from the Exo-S, Exo-C, and WFIRST-AFTA study preliminary target lists (Spergel et al. 2013; Stapelfeldt et al. 2014; Seager et al. 2015), and found that for a typical star they were sensitive to approximately Saturn-mass planets inside of $a = 1$ au and Jupiter-mass planets inside of $a \approx 3$ au. With our significantly expanded data set and target list, we have improved the sensitivity for a typical star by at least a factor of 2, reaching down to about $0.5 M_S$ at 1 au and about $1 M_S$ at 3 au. Moreover, in the best-case scenario, Howard and Fulton (2016) could detect Neptune-mass planets orbiting at $a = 3$ au, while in the best-case scenario in this study we could reach planets at the same semimajor axis down to $\sim 10 M_\oplus$. We note that, while the target lists analyzed in this study and in Howard and Fulton (2016) are not identical, both target lists were compiled with similar criteria and have many targets in common. The improvement in search completeness in this work is predominantly driven by the increase in HIRES/Keck observations since 2014 and the inclusion of archival RVs from additional spectrographs.

While Howard and Fulton (2016) focused on stars in the northern hemisphere sky, a subsequent study by L23 conducted a similar analysis of southern stars. They considered archival Doppler measurements of 52 potential DI mission target stars from the NASA/NSF EPRV Working Group’s list of high-priority stars for future DI missions (Crass et al. 2021). Using RV data from HARPS/ESO, HIRES/Keck, UCLES/AAT, PFS/Magellan, and Levy/APF, L23 demonstrated a lack of sensitivity to Saturn-mass planets in the HZ for most of their targets. In this study, we have shown that a Saturn-mass planet could be detected in the HZ for over half of the targets. This improvement in sensitivity is again driven by the addition of archival RVs from more spectrographs in this study.

Habitable Zone RV Sensitivity Limits

Understanding the current sensitivity of RV observations of nearby stars is critical for the early development of the HWO target list and overall mission architecture. For the HWO exoEarth survey in particular, we must know if potential target stars have disruptive giant planets in the HZ or if we can rule them out. Even planets as small as $5 M_{\oplus}$ in the HZ can lead to dynamically unstable conditions for any potentially Earth-like planets (Kane and Fetherolf 2023). If a large fraction of otherwise viable HWO targets host disruptive HZ planets, more target stars that are farther away will need to be surveyed, requiring a larger-aperture telescope with a more aggressive coronagraph inner working angle (IWA). Therefore, the more targets with dynamically nonviable HZs we can identify now, the easier it will be to implement engineering changes that will enable HWO to characterize a robust sample of potentially habitable planets.

Using the results from the RV search completeness analysis, we assessed what range of planet masses we are sensitive to in the HZs of 120 potential HWO targets given the available public RVs. From the CL_{50} contours (Figure 4.7), we calculated the $M_p \sin i$ sensitivity limits at the inner edge, middle, and outer edge of the conservative HZ for each star, assuming the “moist greenhouse” and “maximum greenhouse” limits from classic 1D radiative–convective climate models (Kasting et al. 1993; Kopparapu et al. 2013).

For Earth-like planets with H_2O - and CO_2 -dominated atmospheres, Kopparapu et al. (2013) derived the following parameterization for the HZ flux limits around main-sequence stars:

$$S_{\text{eff}} = S_{\text{eff},\odot} + aT_{\star} + bT_{\star}^2 + cT_{\star}^3 + dT_{\star}^4, \quad (4.5)$$

where $S_{\text{eff},\odot}$ is the effective incident flux corresponding to a particular HZ definition for a solar twin (i.e., moist greenhouse or maximum greenhouse), $T_{\star} \equiv T_{\text{eff}} - 5780$ K, and a , b , c , d are empirically-determined coefficients.

We calculated S_{eff} at the middle of each star’s HZ (MHZ) by averaging the S_{eff} values at the inner edge of the HZ (IHZ; moist greenhouse limit) and the outer edge of the HZ (OHZ; maximum greenhouse limit). Using stellar properties from the SPORES-HWO Catalog (Harada et al. 2024), the corresponding IHZ, MHZ, and OHZ distances were then computed from the stellar luminosity as

$$a_{\text{HZ}} = \sqrt{\frac{L_{\star}/L_{\odot}}{S_{\text{eff}}/S_{\oplus}}} \text{ au}. \quad (4.6)$$

For each star, we then recorded the CL_{50} sensitivity limits in both $M_p \sin i$ ($M_{\oplus}$) and RV semi-amplitude K (m s^{-1}) corresponding to the IHZ, MHZ, and OHZ distances. As a more conservative estimate of the sensitivity limits, we also recorded the CL_{90} sensitivity limits (i.e., those corresponding to the search completeness contour of 90% detection probability).¹⁹ The IHZ, MHZ, and OHZ distances, corresponding orbital periods, CL_{50} sensitivity limits, and CL_{90} sensitivity limits are listed for each star in Table 4.A7 in this chapter’s appendix.

¹⁹We caution that the CL_{90} limits tend to be more sensitive to the number of injection trials than the CL_{50} limits. In the limit of a very large number of injection trials, we expect the CL_{90} limits to decrease slightly and become closer to CL_{50} . Here, we default to using CL_{50} for all discussions of the mass sensitivity limits.

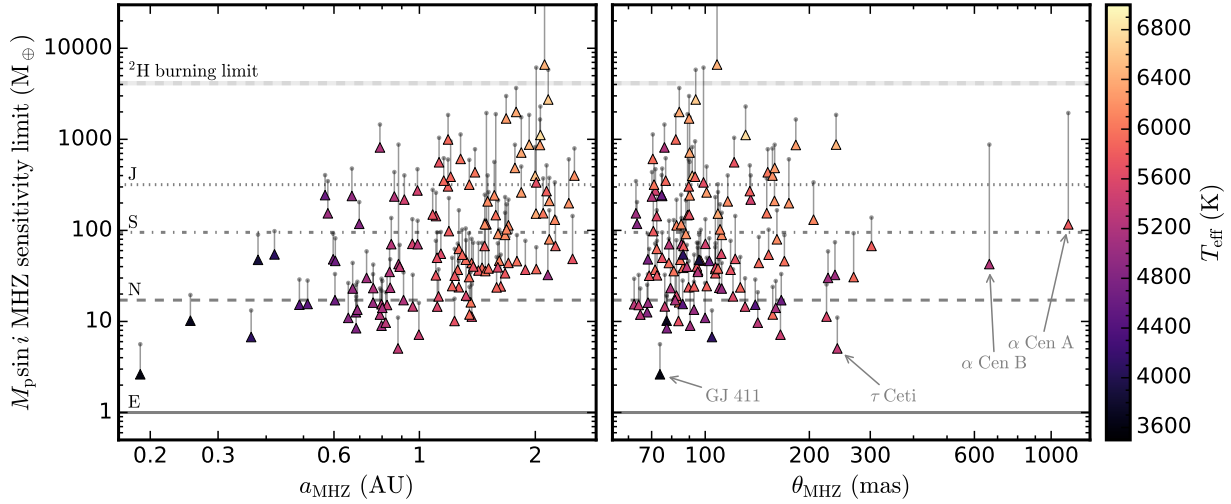


Figure 4.8: Lower $M_p \sin i$ sensitivity limits in the middle of the conservative HZ (Kasting et al. 1993; Kopparapu et al. 2013) derived from the CL_{50} lines shown in Figure 4.7. More conservative sensitivity estimates are shown by the black points and vertical lines, which have been derived from the CL_{90} contours. The sensitivity limits are shown as a function of the physical separation (left) and maximum angular separation (right) of the middle of the conservative HZ defined in instellation space. The points are colored by stellar effective temperature. The sensitivity limit values shown here, in addition to sensitivity limits computed for the IHZ and OHZ, are listed in Table 4.A7 in the appendix.

Figure 4.8 shows the CL_{50} and CL_{90} sensitivity limits for each star as a function of the MHZ distance and maximum angular separation. Each marker indicates the minimum $M_p \sin i$ that could be detected for a circular orbit with 50% probability in a given system’s MHZ, and the corresponding point connected by a vertical line indicates the minimum $M_p \sin i$ that could be detected with 90% probability. The median sensitivity limits for the IHZ, MHZ, and OHZ are $42 M_\oplus$, $48 M_\oplus$, and $61 M_\oplus$, respectively (or, in terms of RV semiamplitude, 3.9 , 4.0 , and 4.3 m s^{-1}). For the more conservative estimates (CL_{90}), the median sensitivity limits are $90 M_\oplus$, $104 M_\oplus$, and $144 M_\oplus$ for the IHZ, MHZ, and OHZ, respectively (or 8.1 , 8.2 , and 9.0 m s^{-1} in RV semiamplitude).

Ignoring dynamical constraints and factors of $\sin i$, the RVs analyzed in this work can rule out noneccentric Jupiter-mass planets in the MHZ for 95 of the 114 systems (83.3%) without known, undisputed planets in their conservative HZs (we discuss systems with known HZ planets later in this section). We can similarly rule out Saturn-mass and Neptune-mass planets in the MHZ for 71 (62.3%) and 24 (21.1%) systems, respectively.²⁰ We are unable to rule out Earth-mass or smaller planets in any of the stars’ HZs. Considering the 44 additional targets that were not analyzed in this work due to insufficient data, this means that up to 63 (38.4%) of the 164 potential HWO target stars could have hidden Jovian planets in their HZs. Moreover, up to 87 (53%) could have

²⁰Taking the more conservative CL_{90} sensitivity limits in the MHZ, we can rule out Jupiter-mass planets for 76 systems, Saturn-mass planets for 55 systems, and Neptune-mass planets for 3 systems.

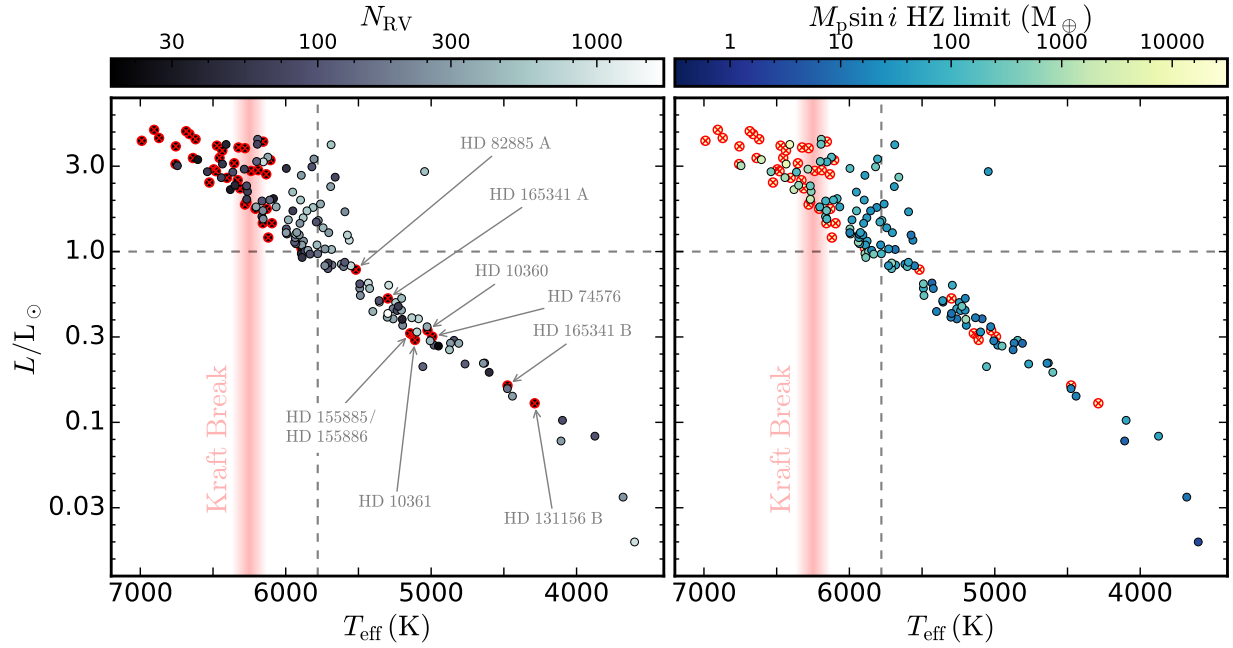


Figure 4.9: H–R diagrams of the 164 target stars with color indicating the number of RV epochs (left) or the lower mass sensitivity limit in the MHZ (right). Stars with fewer than 20 epochs of RV observations are marked with a red “ $\otimes$ ” in both panels. Solar values are shown by the thin dashed lines, and the approximate effective temperature corresponding to the Kraft Break (~ 6250 K; Kraft 1967) is indicated by the transparent red line. The stellar properties shown here are from the SPORRES-HWO Catalog (Harada et al. 2024).

undetected Saturns, and up to 134 (81.7%) could have undetected Neptunes in their HZs.

Figure 4.9 shows H–R diagrams of the target stars, demonstrating how the number of RV epochs and MHZ sensitivity limits are related to stellar properties. It is clear that stars hotter than ~ 6250 K and stars with stellar companions tend to have far fewer RV observations than cooler stars, and therefore tend to have worse (or absent) constraints on planets in the HZ. Cooler stars, in addition to being more amenable to high-precision RV observations, have the added benefit of closer-in HZs where planets are easier to detect. We discuss how stellar properties relate to the sensitivity limits in more detail in the next subsection. In addition to the stellar properties and the number of RV observations, the RV sensitivity can also depend on observing strategy parameters such as the survey cadence and baseline. For example, Figure 4.A3 in the appendix shows the correlations between the number of RV measurements, the total observing duration, and the MHZ sensitivity.

The two systems whose HZ planets we would be most sensitive to are HD 10700 (τ Ceti) and HD 95735 (Lalande 21185; GJ 411). The star τ Ceti is a Sun-like G8V star, which has been studied extensively over the last several decades (see Appendix 4.C)—with 1692 nights of RVs, this was the most extensively observed star in our sample. In τ Ceti’s HZ (0.72–1.25 au), we can rule out planets more massive than 4.4–6.5 $M_{\oplus}$ (or, more conservatively, planets more massive than

9.5–13.9 $M_{\oplus}$). Lalande 21185, an M2V star, is the coolest star in the sample and has also been extensively observed (see Appendix 4.B). The fact that Lalande 21185 is a cool star means that its HZ is closer in, where RV observations are more sensitive to lower-mass planets. With 921 RV epochs, including 297 from Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs (CARMENES), we are sensitive to planets more massive than 2.3–3.6 $M_{\oplus}$ (more conservatively, 4.8–7.6 $M_{\oplus}$) in Lalande 21185’s HZ (0.15–0.28 au).

As stated at the beginning of this section, these companion mass sensitivity limits are crucial for informing trade studies of HWO’s architecture and guiding future precursor science observations of potential target stars for HWO’s exoEarth survey. Additionally, these mass constraints provide key priors on any HZ planets that HWO will discover in the future, significantly aiding the atmospheric modeling required to interpret spectra that HWO measures (e.g., Damiano et al. 2025). While providing specific recommendations for future DI missions like HWO is beyond the scope of this work, we encourage the community to apply the sensitivity limits provided in Appendix Table 4.A7 to coordinate future observing efforts to better understand the planetary systems of potential HWO targets.

Neglected Target Stars

While the majority of target stars ($\sim 73\%$) had at least 20 epochs of public RV data, we emphasize that 21 stars had $0 < N_{\text{RV}} < 20$ (Figure 4.3), and we were unable to obtain any public RVs for 23 stars (Appendix Table 4.A8). We refer to these 44 underobserved stars as the neglected sample.²¹ All of these stars fall into at least one of the following categories: (1) hot stars, (2) highly active stars, or (3) binary stars. We speculate that previous RV surveys tended to exclude or deprioritize stars belonging to these categories because they were less favorable targets for the science goals they were aiming to achieve. We note there was also at least one case of a star having been observed, but those RVs were not accessible apart from a single figure in the discovery paper (HD 33564; see Appendix 4.C).

The left-hand side H–R diagram in Figure 4.9 shows that hot stars ($T_{\text{eff}} \gtrsim 6250$ K) tend to have few or zero RV observations, which leads to worse or nonexistent mass sensitivity limits in the right-hand side H–R diagram. Cooler stars with few or no observations tend to be in multistar systems (e.g., 36 Oph, 70 Oph, ρ Eri), or have unusually high levels of SA, indicated by R'_{HK} (e.g., HD 74576). Figure 4.10 shows the joint distribution of R'_{HK} and T_{eff} , as well as the number of RV epochs for each target star. Stars with at least 20 nights of RVs have a median effective temperature of 5731 K and median R'_{HK} index of -4.9 , which are close to solar values. On the other hand, stars with fewer than 20 RVs have a higher median effective temperature of 6280 K and a higher median R'_{HK} index of -4.575 .

High levels of SA can complicate RV searches for planets (as discussed in Section 3.3), which could partly explain why stars with high R'_{HK} have not been studied as closely as less active stars.

²¹We note that the middle cluster of modestly observed stars in Figure 4.3 would also benefit from additional RV observations.

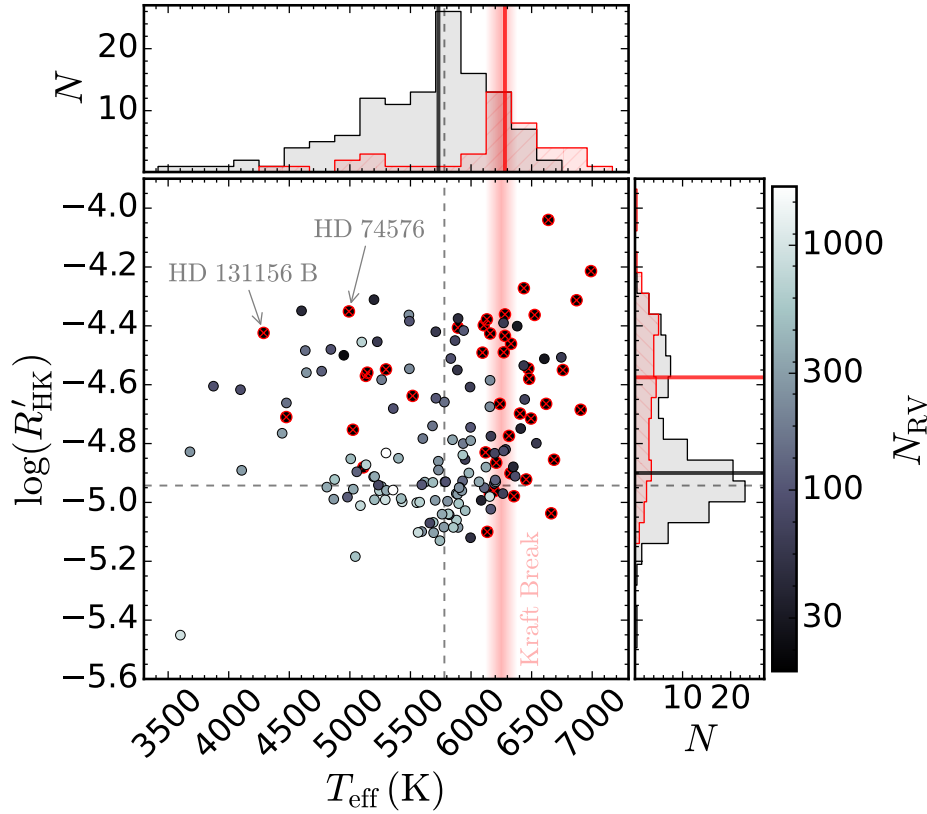


Figure 4.10: Stellar effective temperature vs. $\log R'_{\text{HK}}$. The color scale corresponds to the number of RV observation epochs. Targets with fewer than 20 RV epochs are marked by a red “ $\otimes$ ” symbol. The shaded 1D histograms above and to the right distinguish between targets with at least 20 RV epochs (black) and those with fewer than 20 RV epochs (red). The median 1D histogram values are indicated by solid lines. The approximate location of the Kraft Break temperature is shown by the transparent red line, and solar values are shown by the dashed lines ($\log R'_{\text{HK}} = -4.943$; Egeland et al. 2017).

Certain binary star systems can also be challenging for RV surveys because of slit placement. For binary systems in which both stars are similar in brightness, special attention is required to isolate the spectrum of one component of the star system from the other to avoid blending.

It is also common that RV surveys exclude stars with effective temperatures near or above the Kraft Break (~ 6250 K Kraft 1967), as these hot stars tend to rotate faster, resulting in more strongly Doppler-broadened spectral line profiles and hence lower-precision RV measurements (e.g., Beatty and Gaudi 2015). We note that the precise definition of the Kraft Break varies in the literature²² and is not strictly a single value (e.g., Beyer and White 2024), but it is typically quoted at $T_{\text{Kraft}} = 6250$ K (e.g., Santos et al. 2021; Avallone et al. 2022). This is the value we adopted in

²²The original Kraft (1967) study does not actually provide a specific value of T_{eff} , despite that paper being often cited in the literature for a specific effective temperature.

Figures 4.9 and 4.10. The median number of observations for stars hotter than this definition of the Kraft Break is 14 RVs, while the median number of observations for stars cooler than the Kraft Break is 221 RVs.

While the neglected sample was not included in previous RV surveys, we advocate for future RV programs to include these stars in coordinated multiyear observing campaigns. We also advocate for additional community-coordinated RV observations of the stars with only “moderate” observing history (i.e., those near the middle histogram peak of Figure 4.3). Even if observations of these stars are not precise enough to detect the lowest-mass planets, long-term RV monitoring will still be useful for constraining massive long-period companions and measuring stellar magnetic activity cycles.

Continuing to prioritize the most optimal targets for RV monitoring will cause us to miss out, not only on potentially new and interesting science, but also critical precursor limits on the dynamical viability of the HZs of potential HWO targets. Having no prior knowledge of the planetary systems around roughly a quarter of the HWO target stars would be a significant risk to the mission. Moreover, because $\sim \text{m s}^{-1}$ precision may not be possible for many of the neglected stars, they are ideal targets for lower-precision instruments that are less highly oversubscribed. While state-of-the-art EPRV spectrographs are necessary to achieve $10\text{--}30 \text{ cm s}^{-1}$ precision for detecting very small planets (e.g., Échelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations, hereafter ESPRESSO, KPF, EXPRES, NEID; Pepe et al. 2007; Gibson et al. 2016; Jurgenson et al. 2016; Schwab et al. 2016), such high precision is not needed to achieve the science goals for the neglected sample stated here.

Architectures of Potential ExoEarth Hosting Systems

Although the defining goal of HWO is to detect and characterize exoEarths as living worlds, HWO is being designed to be a versatile facility that will revolutionize many aspects of astrophysics. In exoplanetary science, HWO will give unprecedented insights into the diversity of planetary system architectures and help to place the solar system in context. For example, the exquisite sensitivity, IWA, and contrast requirements for imaging Earth-analogs will make HWO a premier facility for spectroscopically characterizing hundreds of cool outer planets with a wide range of masses, orbital characteristics, atmospheric compositions, dynamical histories, and other properties. Opening this new parameter space will change our understanding of cool planet demographics, planet formation, and dynamical evolution. Because HWO will also discover Earth-analog exoplanets in these systems, it will enable us to start addressing questions like “Is the particular architecture and dynamical history of the solar system a prerequisite for habitability?” and “How common are Earth-like planets in systems with architectures significantly different from our solar system?”

RV surveys have thus far already demonstrated a rich diversity of planets and planetary system architectures among potential target stars for HWO. However, the knowledge we can gain of these systems from RVs is still incomplete. Not only are many potential HWO targets lacking RV observations (as discussed in the previous subsection), but there are many cases of disputed planetary signals or new RV PCs that need confirmation.

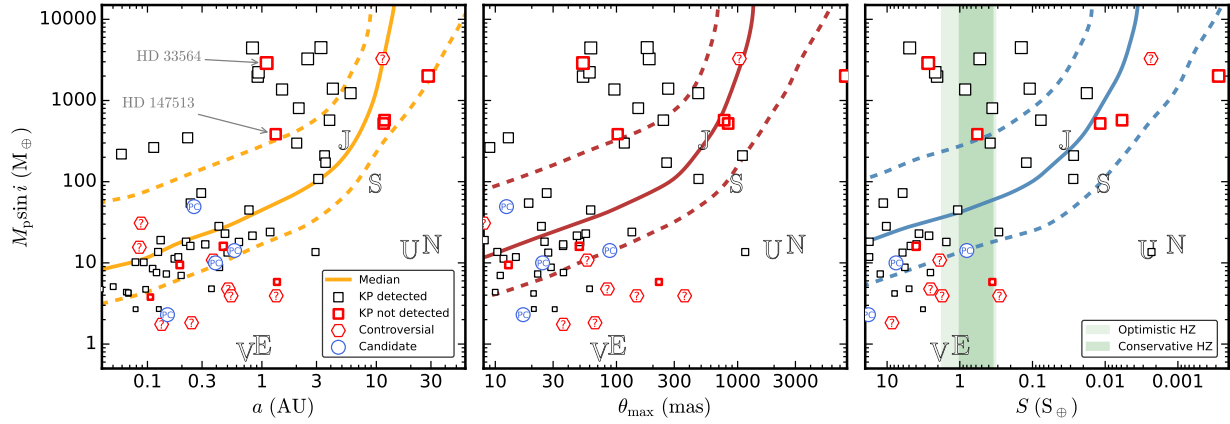


Figure 4.11: Known exoplanets in the target sample as a function of $M_p \sin i$, semimajor axis, maximum angular separation (assuming circular orbits), and incident stellar flux. The sizes of the squares also correspond to the relative $M_p \sin i$. The median CL₅₀ limits (Figure 4.7) are shown by the solid colored lines, and the middle 68% of CL₅₀ limits are bounded by the dashed colored lines. Previously detected planets that were not detected in this study are indicated by red squares, and the locations of the solar system planets are labeled by the first letter of each planet. The green shaded regions in the right panel show the conservative and optimistic habitable zone limits in instellation space.

Figure 4.11 shows the 70 known planets in the sample (in 30 different systems) as a function of a , $\theta_{\max}$, and S . We detected and updated the properties of 51 of these known planets in addition to 4 PCs (and 2 known stellar companions) with the RVs analyzed in this study. We note that at least nine previous planet claims have been disputed (labeled as controversial in Figure 4.11). The disputed planets and the 10 other previously known planets that were not detected in this work are summarized in Appendix Table 4.A6.

The known planets in the sample represent a wide range of masses, semimajor axes, and radiation environments. Although knowing the true masses of these planets requires knowledge of the orbital inclination (which RVs alone are not sensitive to), if we assume that most systems have inclinations close to $i = 90^\circ$, then sub-Neptunes ($M_p < 17 M_\oplus$) account for 28 (46%) of the undisputed known planets,²³ of which 15 are super-Earths ($2 M_\oplus < M_p < 8 M_\oplus$). Those planets receive between $0.0023\times$ and $2665\times$ as much stellar flux as the Earth, and their semimajor axes range from 0.015 to 2.94 au.

The next largest group of planets is super-Jupiters ($M_p > 318 M_\oplus$), which account for 17 (28%) of the undisputed planets. These planets receive between 1.9×10^{-6} and 36 times as much stellar flux as the Earth and orbit their stars at distances ranging from 0.225 to 773 au.

²³Although most of these known planets do not have measured inclinations, we can estimate how the $\sin i$ degeneracy effects true planet masses in a statistical sense. Assuming orbits are oriented randomly, the inclination of any given system has a probability density function of $dp/di = \sin i$. Integrating dp/di from 30° to 90° , we find that the probability of a system's inclination being within that range is about 86.6%. Therefore, the $\sin i$ degeneracy correction factor should be < 2 ($= 1/\sin 30^\circ$) for about 86.6% of systems shown in Figure 4.11.

Super-Neptunes/sub-Saturns ($17 M_{\oplus} < M_p < 95 M_{\oplus}$; $N = 10$) and Jovian planets ($95 M_{\oplus} < M_p < 318 M_{\oplus}$; $N = 6$) make up the rest of the undisputed planets. The super-Neptunes/sub-Saturns receive $0.29\text{--}68.5\times$ the flux received by Earth and orbit at semimajor axes of $0.13\text{--}1.18$ au, while the Jovians receive $0.027\text{--}956\times$ the flux at Earth and orbit their stars at $0.059\text{--}3.6$ au. Most of the controversial or disputed planets (seven out of nine) are smaller than Neptune, and the smallest (τ Ceti g; see Appendix 4.C) has a putative mass of $1.75 M_{\oplus}$ (Feng et al. 2017b).

Figure 4.12 shows the architectures of all target systems with at least one known planet or PC, in addition to the CL_{50} sensitivity limits as a function of the semimajor axis. More than half of the target stars (16 out of 30) with known planets are multiplanet systems with at least two undisputed planets. At least 11 of those systems have a planet multiplicity of 3 or more, and the highest-multiplicity systems each have at least five planets: HD 219134 (Section 4.5) and 55 Cancri (Appendix 4.B). None of the known architectures of these systems are consistent with the solar system.

While none of the known planets are exact analogs of any of the solar system planets, an interesting exercise is to see whether it would be possible to detect solar system analogs in any of these systems given our sensitivity limits. Using the CL_{50} contours in Figure 4.7, we determined that we could detect a Jupiter-analog (in terms of semimajor axis) in about 69 of the 120 systems (57.5%), and a Saturn-analog in about 7 systems (5.8%). No other solar system planets would be detectable. If we assume the more conservative sensitivity limits (i.e., using the CL_{90} instead of the CL_{50}), then only 30 Jupiters and no Saturns would be detected.

If instead we define the solar system analogs in terms of instellation flux to account for differences in stellar spectral types across the sample, we find similar but slightly more optimistic results. In terms of S , we could detect a Jupiter in about 68 systems (56.7%) and a Saturn in about 18 systems (15%). Using the more conservative limits, we could detect Jupiter in about 45 systems (37.5%) and Saturn in about 4 systems (3%). Again, no solar system planets smaller than Saturn would be detectable.

Finally, we note that six systems have at least one undisputed planet in the conservative HZ (assuming circular orbits), and eight have at least one undisputed planet in the optimistic HZ (the “early Mars” and “late Venus” limits; Kasting et al. 1993; Kopparapu et al. 2013). The HZ planets include HD 69830 d, 55 Cnc f, 82 Eri f, μ Ara b, q1 Eri b, 47 UMa b, v And d (Appendix 4.B), and HD 147513 b (Appendix 4.C). The candidate HD 219134.04 (Section 4.4) is would also orbit in the HZ. All of these planets are more massive than the Earth, ranging in $M_p \sin i$ from $5.8 M_{\oplus}$ to $1370 M_{\oplus}$, and therefore decrease the dynamical viability of the HZ for hosting potentially habitable Earth-like planets.

While dynamical simulations of these systems are beyond the scope of this paper, previous dynamical studies of the 164 stars considered in this work found that the HZs of 11 planet hosts are $< 50\%$ dynamically viable due to giant planets whose orbits pass near or through the HZ (Kane et al. 2024). The impact of stellar and planetary uncertainties on the dynamical influence of HZ perturbors is also discussed in Kane and Burt (2024). Alarmingly, as many as 63 (38.4%) of the 164 EMSL target stars could have undetected Jovian planets in their HZs. Saturn- and Neptune-mass planets, which also negatively impact the dynamical viability of the HZ, could also be hiding in up to 53% and 82% of the stars’ HZs given the current RV sensitivity limits. This

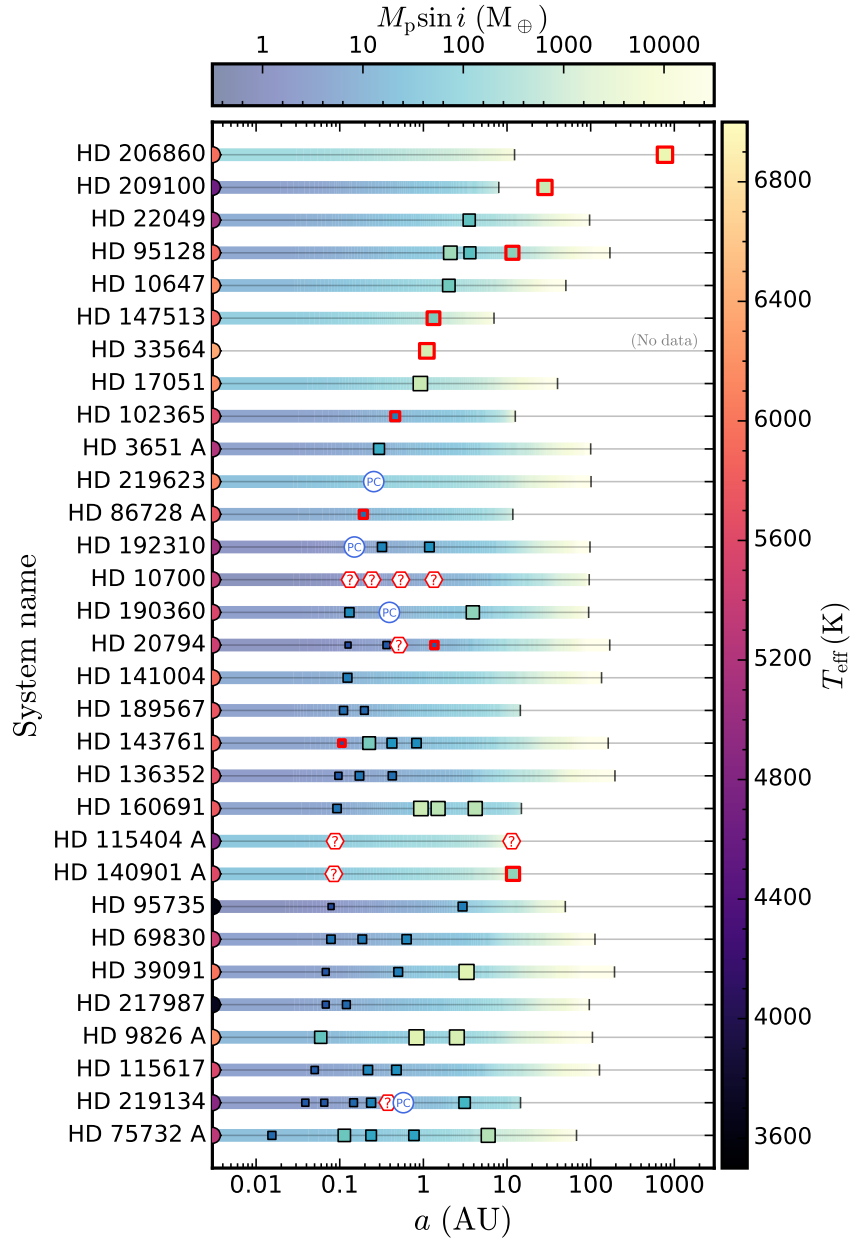


Figure 4.12: Architectures of systems in our sample with at least one known planet or PC. Both the color and size of each marker correspond to $M_p \sin i$. Markers that are outlined in red show the known planets that were not detected in this study. Disputed planet detections are shown as red “?”s inscribed in hexagons, and planet candidates are indicated by blue circles with the text “PC.” Each colored horizontal line shows the minimum $M_p \sin i$ sensitivity limit (from the CL₅₀) as a function of semimajor axis, and the colored circles on the left-hand side show stellar effective temperature. Note that HD 33564 has no sensitivity limits because no public RV observations were available.

poses a significant challenge to HWO that must be addressed through additional precursor RV observations of potential exoplanet DI target stars. Such observational efforts must begin as soon as possible to build up the RV sensitivity to giant HZ planets before a final architecture for HWO is decided.

4.7 Conclusions

In this chapter, we have presented a uniform analysis of over 35 yr of archival RV observations of 120 potential target stars for future exoplanet DI missions such as HWO. We analyzed over 150,000 RV measurements to search for planetary signals, refine the orbits and properties of KCs, identify false positives, and determine sensitivity limits on companion masses. Our main conclusions are as follows.

1. Over 35,000 epochs of high-precision ($\lesssim 10 \text{ m s}^{-1}$) RV observations (153,902 total unbinned measurements) have been made of 141 potential HWO target stars from the EMSL and SPORES-HWO Catalog (Mamajek and Stapelfeldt 2024; Harada et al. 2024). Public RV observations of these stars span over 36 yr, going as far back as 1987, and were observed by 23 different high-resolution spectrographs located across the globe. To obtain the most complete and accurate data set possible, we created the SPORES-HWO RV Hunters community science project to reliably collect, organize, and vet public RVs and SA indicator data from 40 different public sources.
2. Analyzing the periodograms of the RVs and SA data for 120 stars (with $N_{\text{RV}} \geq 20$), we identified and modeled 109 periodic RV signals in 49 unique systems. We associate 51 signals with previously known planets and 2 signals with known stellar companions, hence providing revised orbital parameters for those companions. Of the other signals, 26 are associated with known SA, and 19 are likely systematic FAs. Additional observations or analyses are needed to confirm the nature of the remaining 11 signals, of which 4 are likely PCs. We also fit either linear or quadratic trends to the RVs in 74 systems, which may be caused by known stellar binaries or indicate the presence of unseen long-period companions.
3. We derived sensitivity limits on companion masses for 120 stars from the results of planet injection-recovery simulations. The lower mass sensitivity limit for a typical star in the sample is approximately $50 M_{\oplus}$ for a 1 au circular orbit. For most of the sample (the middle 68% of stars), the lower mass sensitivity limit at 1 au is between about 1 Neptune-mass ($17 M_{\oplus}$) and 1 Jupiter-mass ($318 M_{\oplus}$). In the best case, a $\sim 6 M_{\oplus}$ planet would be detectable at 1 au around a quiet host star, while, in the worst case, even planets larger than $10 M_{\text{J}}$ would not be detectable at 1 au. These mass limits are a significant improvement over limits derived in previous studies (Howard and Fulton 2016; L23) in terms of the typical sensitivity achieved, the number of targets analyzed, and the scope of RV and SA data.
4. The mass sensitivity limits for the conservative HZ, which depends on stellar spectral type, are about $42 M_{\oplus}$ at the IHZ and $61 M_{\oplus}$ at the OHZ for a typical star in the sample. Including

the stars that did not have enough observations to be analyzed, the HZ sensitivity limits suggest that up to 63 (38.4%) of the 164 potential HWO target stars on the EMSL could be hiding undetected disruptive Jovian planets in their HZs. The outlook is worse for lower-mass HZ perturbers. We cannot rule out Saturn-mass planets in the HZs of up to 87 (53%) of the EMSL targets, or Neptune-mass planets in the HZs of up to 134 (81.7%) of the targets.

5. While some of the EMSL target stars have already been thoroughly studied by past RV surveys (Figure 4.3), as many as 21 stars have fewer than 20 RV observations, and as many as 23 have no publicly available RV data. These neglected stars are typically either hot (near or above the Kraft Break), are highly active, or belong to multistar systems. Because stellar noise is likely the limiting factor of RV precision for these targets, we advocate for community-coordinated observing campaigns to monitor the Doppler motions of these stars using moderate- to high-precision RV facilities ($\sigma_{\text{RV}} \gtrsim 1 \text{ m s}^{-1}$). Such instruments are well suited for the long-baseline observations required to measure giant planet masses in the HZ, and are far less likely to be oversubscribed than EPRV resources.
6. We identified six RV signals that are either PCs or sources requiring confirmation. During the revision stage of this paper, one of these candidates (HD 190360 d; Section 4.5) was confirmed to be planetary in nature (Giovinazzi et al. 2025b). Further observations and analysis are needed to determine the origin of the putative signals in HD 192310, τ PsA, Lacaille 9352, HD 219134, and HD 219623.
7. While 70 planets have previously been reported in 30 of the target systems, we note that at least 9 reported planets have been disputed or were not detailed in the original discovery papers (Appendix Table 4.A6). We advise caution in taking these planet detections at face value, and recommend follow-up studies to properly classify the disputed signals. This is critical because some of the disputed planets have orbits in or near the HZ, which could preclude those systems from hosting Earth-analogs if the planets turn out to be real.
8. We emphasize that HD 165499 (ι Pav) and HD 212330 A (Appendix 4.B) have unresolved stellar companions at $< 1''$ of angular separation (e.g., Barbato et al. 2023). However, ι Pav was not flagged as a binary star in the EMSL, and HD 212330 A was listed in the EMSL with inaccurate WDS companion properties. In fact, neither system should have been included in the EMSL based on the criteria for binary stars set by Mamajek and Stapelfeldt (2024), as they excluded any binary stars separated by $< 3''$. We therefore advise caution in including these systems in future studies of potential HWO targets.
9. Lastly, we have created a set of 120 human-readable LaTeX summary reports for each system we analyzed. Each file contains the RVSearch summary (e.g., Figure 4.4) and completeness plots (e.g., Figure 4.5), SA GLS periodogram plots (e.g., Figure 4.6), and MCMC posterior corner plots (e.g., Figure 4.A1–4.A2), in addition to several tables summarizing the data, significant RVSearch signals, MCMC posteriors, and derived planet properties. The full set of LaTeX reports for each system are published along with the complete figure sets, machine-readable tables, and all RV and SA data on Zenodo (see footnote 6).

The aggregation of decades of RV data and determination of HZ sensitivity limits presented in this work are an important step toward realizing a high-contrast DI space telescope capable of resolving Earth-like planets in nearby HZs. However, there is a long road ahead to the first direct detection of a habitable world beyond the solar system, and understanding the planetary system architectures of potential exoEarth hosts is just one important element of the precursor science needed to make HWO successful.

We make two final recommendations based on the findings of this work. First, we recommend the creation and ongoing maintenance of a public repository for RV measurements of future exoplanet DI mission targets. This would be an extremely powerful resource for the exoplanet community to coordinate new RV observations (whether related to HWO precursor science or not) and utilize limited observing resources as efficiently as possible. We encourage observers to publish and document their RV data sets, especially for targets with nondetections, and add them to the database.

Second, we advocate for community-coordinated RV observations of the neglected sample of potential HWO target stars. All of the data and analysis products presented in this work are available to download and are intended to provide guidance for future observing campaigns. Historically undersubscribed RV facilities will be especially valuable for precursor HWO studies because extremely high-precision measurements are not needed to rule out long-period giant planets in the HZs of these systems.

Appendix

4.A Additional Figures and Tables

Here, we include large figures and tables that were not shown in the main text. Figures 4.A1 and 4.A2 show the MCMC posterior distributions of the RV model parameters for HD 190360 (shown in Figure 4.4). Figure 4.A3 shows the correlations between the minimum mass sensitivity limits in the MHZ, the number of RV observations, and the baseline of RV observations for each target. Table 4.A1 contains information for each star in our sample with at least one RV measurement, including stellar effective temperature, the number of SA indicators measured, the number of epochs of RV observations, and the start date and time span of the RV observations. Table 4.A2 details the observatories and instruments that collected the data used in this work. Table 4.A3 shows a subset of the data used in this work (for HD 190360 as an example), including the RVs and SA data. Table 4.A4 lists all of the Keplerian RV signals detected with RVSearch, including best-fit parameters such as P , K , e , ω , a , and $M_p \sin i$, in addition to the detection FAP and the classification of each signal. Table 4.A5 lists trends detected by RVSearch and the associated best-fit trend terms, $\dot{\gamma}$ and $\ddot{\gamma}$. Table 4.A6 shows the properties of the known planets (or disputed planets) in the sample, which were not detected in this work. Table 4.A7 lists all of the derived RV sensitivity limits corresponding to the IHZ, MHZ, and OHZ in terms of $M_p \sin i$ and RV semiamplitude K . Lastly, Table 4.A8 lists the target stars for which we found no public RV observations.

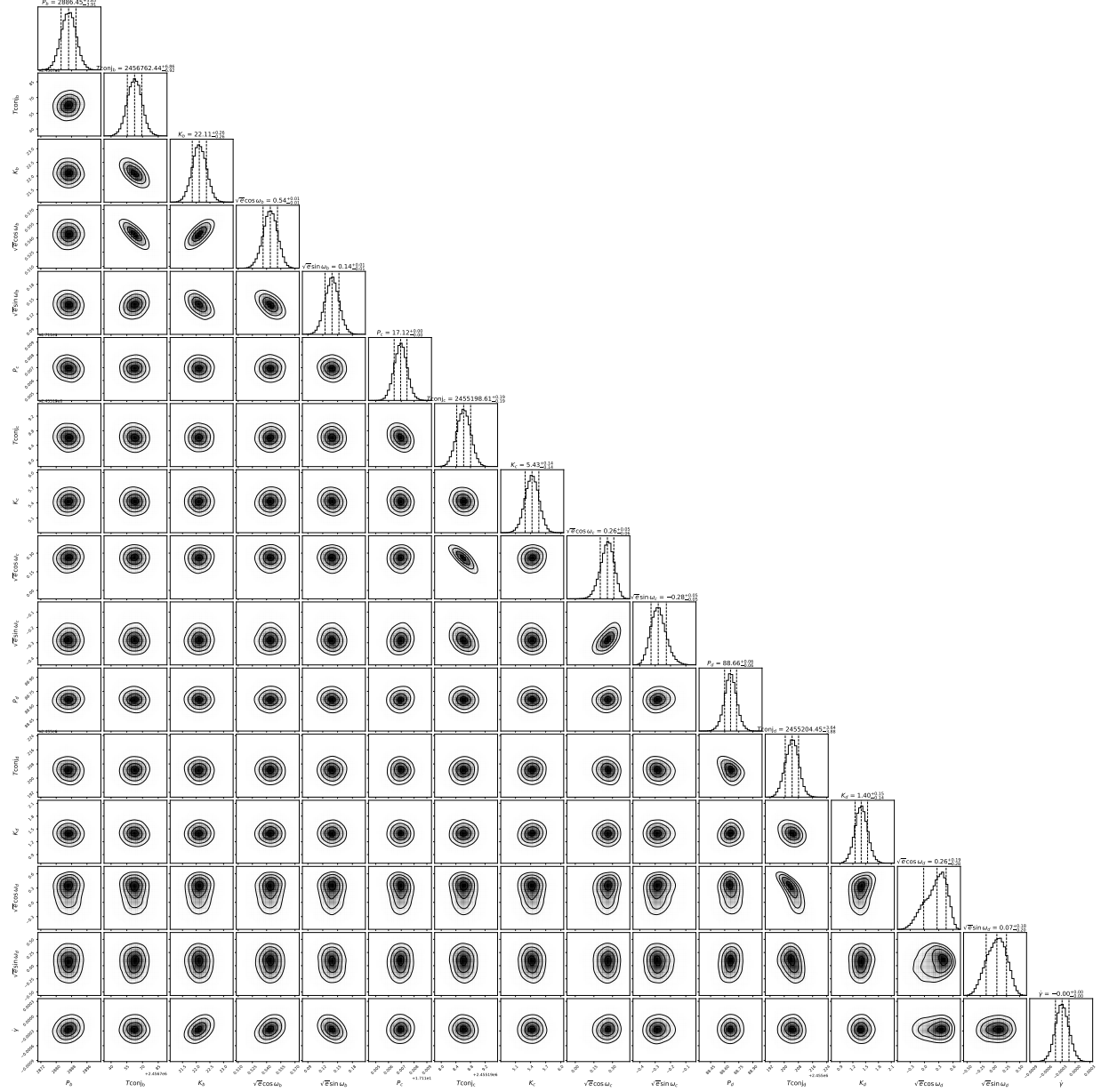


Figure 4.A1: Example MCMC posterior corner plot demonstrating convergence of the three planet Keplerian model for HD 190360 shown in Figure 4.4.

(The full set of 74 corner plots for all systems with RV detections and/or RV trends can be accessed online in Harada et al. (2025) at the publisher's website.)

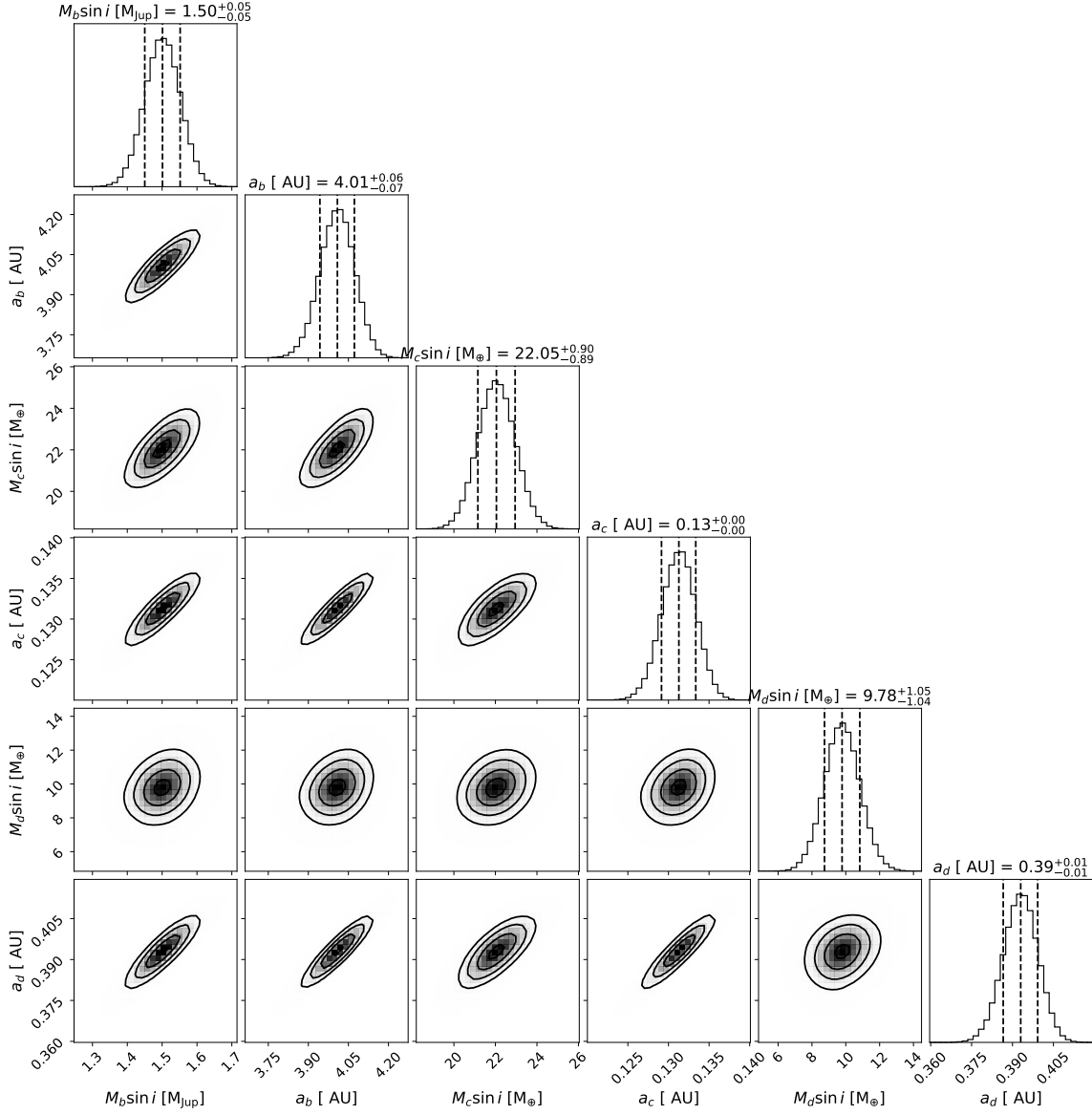


Figure 4.A2: Same as Figure 4.A1, but for the derived planet parameters $M_p \sin i$ and a .

(The full set of 49 corner plots for all systems with RV detections can be accessed online in Harada et al. (2025) at the publisher's website.)

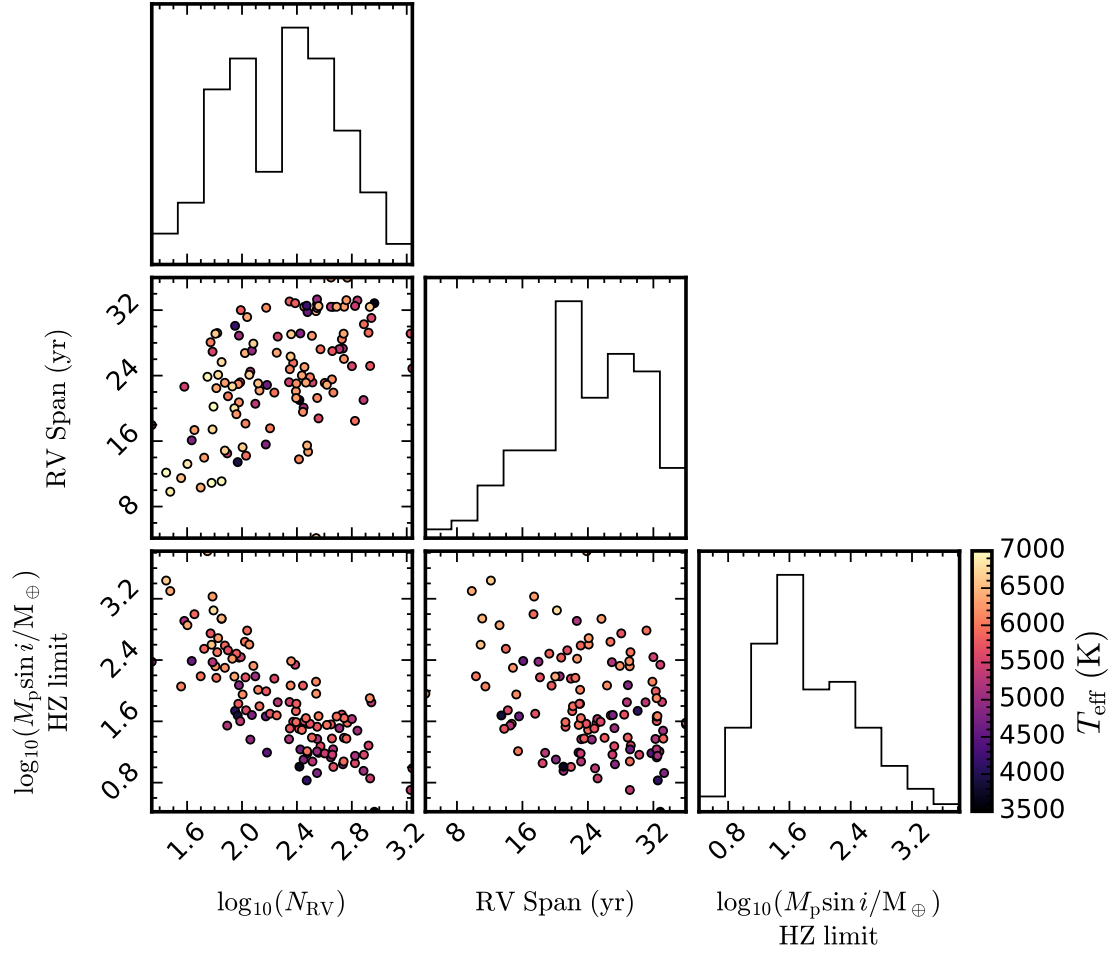


Figure 4.A3: Comparison of the lower $M_p \sin i$ sensitivity limits in the HZ with the number of RV observation epochs and the span of the RV observations for each target. The color scale corresponds to stellar effective temperature.

HD Name	Alt. Name	T_{eff} (K)	Insts.	# RV	# SAI [†]	First	Last	Span (yr)	Refs.
HD 166	V439 And	5491	HIRES-post, Hamilton, Levy	98	53	1987-06-13	2019-06-13	32.0	(19, 31)
HD 693	6 Cet	6190	HARPS-pre	16	64	2005-08-19	2011-07-22	5.9	(26)
HD 1581	ζ Tuc	5932	CES-LC, CES-VLC, HARPS-post, HARPS-pre, UCLES	550	1547	1992-11-03	2021-12-19	29.1	(15, 26, 36)
HD 2151	β Hyi	5806	CES-LC, CES-VLC, HARPS-pre, UCLES	249	232	1992-11-04	2015-11-19	23.0	(15, 26, 36)
HD 3651 A	54 Psc A	5203	HIRES-post, HIRS-pre, HRS, Hamilton, Levy, Tull	461	168	1987-09-09	2020-02-01	32.4	(19, 11, 31)
HD 4391	GJ 1021	5887	CES-LC, CES-VLC, HARPS-pre	53	65	1993-09-16	2007-09-07	14.0	(15, 26)
HD 4614 A	η Cas A (Achird)	5907	HIRES-post, HIRS-pre, Hamilton, Levy, SOPHIE	273	120	1995-09-09	2019-09-17	24.0	(19, 16, 31, 7)
HD 4628	GJ 33	5007	HARPS-post, HARPS-pre, HIRS-pre, Hamilton, Levy	444	398	1987-09-08	2020-02-05	32.4	(26, 19, 31)
HD 5015	GJ 41	6105	HIRES-post, SOPHIE	6	10	2007-01-07	2009-12-02	2.9	(19, 7)
HD 7570	v Phe	6110	CES-LC, CES-VLC, HARPS-pre, UCLES	131	122	1992-11-03	2015-11-21	23.0	(15, 26, 36)
HD 9826 A	v And A (Titawin)	6154	AFOE, ELODIE, HIRS-post, HRS, Hamilton, Levy, SOPHIE, Tull	853	102	1987-09-08	2020-01-31	32.4	(1, 5, 31, 12, 7, 10)
HD 10360	p Eri A	5025	HARPS-post	8	32	2015-11-12	2018-07-17	2.7	(26)
HD 10361	p Eri B	5111	HARPS-post	8	32	2015-11-12	2018-07-17	2.7	(26)
HD 10476	107 Psc	5204	HIRES-post, HIRS-pre, Hamilton, Levy	353	215	1987-09-09	2019-12-10	32.3	(19, 31)
HD 10647	q1 Eri	6155	CES-LC, CES-VLC, CORALIE-07, CORALIE-98, HARPS-post, HARPS-pre, UCLES	226	545	1993-09-16	2020-01-17	26.3	(15, 14, 26, 9)
HD 10700	τ Cet	5356	CES-LC, CES-VLC, CORALIE-07, CORALIE-14, CORALIE-98, EXPRES, HARPS-post, HARPS-pre, HIRS-post, HIRS-pre, Hamilton, Levy	1692	2929	1992-11-03	2021-12-19	29.1	(15, 23, 33, 26, 19, 31)

HD 10780	V987 Cas	5358	HIRES-post, Hamilton, Levy, SOPHIE	97	43	1998-12-05	2022-02-08	23.2	(19, 31, 7)
HD 14412	GJ 95	5401	HARPS-post, HIRES-post, HIRES-pre, Levy, PFS-post, PFS-pre, UCLES	401	444	1996-10-09	2019-11-19	23.1	(26, 19, 31, 36)
HD 16895 A	θ Per A	6263	Hamilton	67	0	1987-09-08	2011-10-12	24.1	(16)
HD 17051	ι Hor	6157	CES-LC, CES-VLC, CORALIE-98, HARPS-post, HARPS-pre, UCLES	228	318	1992-11-04	2021-11-25	29.1	(15, 3, 26, 9)
HD 17925	EP Eri	5199	HARPS-post, HARPS-pre, Hamilton	38	89	1995-02-20	2017-10-13	22.6	(26, 16)
HD 19373	ι Per	5952	HIRES-post, HIRES-pre, Hamilton, Levy	489	181	1987-09-08	2020-02-06	32.4	(19, 31)
HD 20010 A	α For (Dalim)	6195	CES-LC, CES-VLC, HARPS-pre	75	99	1992-11-03	2007-09-07	14.8	(15, 26)
HD 20630	κ 1 Cet	5709	Hamilton, SOPHIE	59	15	1987-09-08	2015-10-06	28.1	(16, 7)
HD 20766	ζ 1 Ret	5710	CES-LC, CES-VLC, HARPS-pre, UCLES	106	152	1997-10-01	2015-11-22	18.1	(15, 26, 36)
HD 20794	82 Eri	5432	ESPRESSO, HARPS-post, HARPS-pre, PFS-post, PFS-pre, UCLES	858	2525	1998-01-17	2023-03-25	25.2	(38, 26, 36)
HD 20807	ζ 2 Ret	5847	CES-LC, CES-VLC, HARPS-post, HARPS-pre, PFS-post, PFS-pre, UCLES	323	675	1992-11-04	2021-09-15	28.9	(15, 26, 36)
HD 22001 A	κ Ret A	6662	HARPS-pre	11	44	2007-10-23	2010-10-30	3.0	(26)
HD 22049	ε Eri (Ran)	5098	CES-LC, CES-VLC, EXPRES, HARPS-post, HARPS-pre, HIRES-post, Hamilton, Levy, Tull	693	552	1987-09-08	2020-11-13	33.2	(15, 32, 26, 19, 31, 8)
HD 22484	10 Tau	5996	HIRES-post, SOPHIE	50	57	2009-10-06	2020-02-01	10.3	(19, 7)
HD 23249	δ Eri (Rana)	5045	CES-LC, CES-VLC, HARPS-post, HARPS-pre, HIRES-post, HIRES-pre, Levy, SOPHIE, UCLES	512	714	1992-11-04	2020-02-02	27.2	(15, 26, 19, 31, 7, 36)
HD 25457	GJ 159	6268	HARPS-post, HARPS-pre, HIRES-post, HIRES-pre, SO-PHIE	61	179	2002-08-29	2020-02-01	17.4	(26, 19, 7)

HD 25998	50 Per	6381	HIRES-post	30	56	2008-12-05	2018-09-28	9.8	(19)
HD 26965 A	40 Eri A (Keid)	5133	HARPS-post, HARES-pre, HIRES-post, HARES-pre, Hamilton, Levy, PFS-post, PFS-pre, UCLES	666	777	1987-09-10	2020-03-14	32.5	(16, 26, 19, 31, 36)
HD 30495	58 Eri	5833	HARPS-post, HARPS-pre, HIRES-post, Hamilton	91	96	2000-10-19	2020-02-01	19.3	(26, 19, 16)
HD 30652	π 3 Ori (Tabit)	6443	HARPS-pre, Hamilton	71	55	2000-09-09	2011-10-12	11.1	(26, 16)
HD 32147	GJ 183	4810	HARPS-post, HARPS-pre, HIRES-post, Hamilton, Levy, PFS-post, PFS-pre	352	466	1987-09-08	2020-12-31	33.3	(26, 19, 16, 36)
HD 32923	104 Tau	5691	HIRES-post, Hamilton, Levy, SOPHIE	313	209	1998-12-05	2022-09-23	23.8	(19, 31, 7)
HD 34411	λ Aur	5854	EXPRES, HIRES-post, HIRES- pre, Hamilton, Levy	576	338	1987-09-10	2020-11-27	33.2	(33, 19, 31)
HD 37394	V538 Aur	5226	HIRES-post, Hamilton, Levy	61	28	1992-01-24	2018-12-28	26.9	(19, 31)
HD 38392	γ Lep B	4950	HIRES-post, HIRES-pre	22	30	2001-11-22	2019-11-08	18.0	(19)
HD 38393	γ Lep A	6313	HIRES-post	6	12	2008-12-05	2013-11-17	5.0	(19)
HD 38858	GJ 1085	5731	HARPS-post, HIRES-post, HIRES-pre, Levy	223	164	1996-12-01	2021-09-13	24.8	(26, 19, 31)
HD 39091	π Men	5982	CORALIE-07, CORALIE-14, CORALIE-98, ESPRESSO, HARPS-post, HARPS-pre, PFS-post, UCLES	415	1085	1998-01-16	2020-12-02	22.9	(27, 26, 36)
HD 43042	71 Ori	6539	Hamilton, SOPHIE	60	31	2000-11-19	2011-10-12	10.9	(16, 7)
HD 43386	74 Ori	6480	HARPS-post, SOPHIE	13	14	2006-12-11	2015-11-20	8.9	(26, 7)
HD 43834 A	α Men A	5594	CES-LC, CES-VLC, HARPS- pre	107	0	1993-03-08	2007-05-25	14.2	(15, 24)
HD 46588 A	GJ 9215A	6204	CARMENES, SONG	347	0	2015-04-03	2019-05-25	4.1	(34)
HD 48682	56 Aur	6066	HIRES-post, Hamilton, Levy	361	106	1987-09-10	2020-03-08	32.5	(19, 31)
HD 50281	GJ 250A	4767	HARPS-pre, HIRES-post, HIRES-pre, Hamilton, Levy	118	154	1993-11-13	2020-11-29	27.0	(26, 19, 31, 36)
HD 50692	37 Gem	5924	HIRES-post, HIRES-pre, Hamilton, Levy	292	151	1997-01-14	2020-03-08	23.1	(19, 16, 31)
HD 53705	GJ 9223A	5790	CES-LC, CES-VLC, HARPS- post, HARPS-pre	94	115	1992-12-16	2015-12-06	23.0	(15, 26)

HD 55575	GJ 1095	5902	HIRES-post, Hamilton, Levy	248	126	1998-12-05	2020-03-08	21.3	(19, 31)
HD 58855	22 Lyn	6349	SOPHIE	40	40	2006-12-18	2020-03-01	13.2	(7)
HD 65907 A	GJ 294A	5997	HARPS-post, HARPS-pre	298	1179	2003-10-30	2019-04-18	15.5	(26)
HD 69830	GJ 302	5423	CES-LC, CES-VLC, HARPS-post, HIRES-post, Hamilton, Levy, PFS-pre, UCLES	455	369	1993-03-09	2020-03-08	27.0	(15, 26, 19, 31, 36)
HD 69897	χ Cnc	6269	Hamilton, SOPHIE	85	16	1987-09-10	2010-05-16	22.7	(16, 7)
HD 72673	GJ 309	5261	HARPS-post, HARPS-pre, HIRES-post, HIRES-pre, PFS-pre, UCLES	326	835	1996-12-01	2020-02-01	23.2	(26, 19, 36)
HD 72905	3 UMa	5893	HIRES-post, HIRES-pre, SO-PHIE	45	68	2002-10-25	2020-03-01	17.4	(19, 7)
HD 75732 A	55 Cnc A (Copernicus)	5292	ELODIE, HARPS-North, HARPS-pre, HIRES-post, HIRES-pre, HRS, Hamilton, Levy, SOPHIE, Tull	876	442	1989-02-21	2020-03-08	31.0	(5, 20, 26, 19, 13, 31)
HD 76151	GJ 327	5780	HARPS-post, HARPS-pre, HIRES-post, Hamilton, Levy	150	200	1989-02-20	2021-06-05	32.3	(26, 30, 16)
HD 78154 A	13 UMa A	6325	SOPHIE	19	19	2008-05-16	2009-04-03	0.9	(7)
HD 78366	GJ 334.2	5992	Hamilton, Levy	66	0	1989-11-16	2019-01-29	29.2	(16, 30)
HD 84117	GJ 364	6163	HARPS-pre, HIRES-post, Levy	101	127	2004-11-29	2020-02-28	15.2	(26, 19, 31)
HD 84737	GJ 368	5893	HIRES-post, Hamilton, Levy	285	119	1995-02-19	2020-03-08	25.0	(19, 31)
HD 86728 A	20 LMi A	5743	HIRES-post, Hamilton, Levy, NEID	445	137	1987-06-13	2023-06-07	36.0	(19, 31, 39)
HD 88230	Groombridge 1618	4097	HIRES-post, Hamilton	89	62	1988-02-03	2018-03-04	30.1	(19, 31)
HD 89449	40 Leo	6410	HARPS-post, HARPS-pre, SO-PHIE	38	76	2007-02-28	2017-06-01	10.3	(26, 7)
HD 90839	36 UMa A	6164	Hamilton, SOPHIE	64	36	1987-12-20	2017-01-29	29.1	(16, 7)
HD 91324	GJ 9332	6155	HARPS-pre	17	59	2006-02-09	2011-02-06	5.0	(26)
HD 95128	47 UMa (Chalawan)	5880	ELODIE, HIRES-post, HIRES-pre, HRS, Hamilton, Levy, SO-PHIE, Tull	585	121	1987-06-13	2023-05-31	36.0	(5, 19, 11, 31, 7)
HD 95735	Lalande 21185	3601	CARMENES, HIRES-post, HIRES-pre, Hamilton, Levy, SOPHIE	921	848	1987-06-12	2020-04-16	32.8	(28, 19, 31, 22)

HD 100623 A	20 Cr A	5196	HARPS-post, HARES-pre, HARES-post, HARES-pre, PFS-post, PFS-pre, UCLES	220	256	1996-12-01	2020-02-10	23.2	(26, 19, 36)
HD 101501	61 UMa	5491	EXPRES, HARES-post, Hamilton, Levy	222	116	1987-06-12	2020-07-02	33.1	(29, 19, 31)
HD 102365	GJ 442A	5618	CES-LC, CES-VLC, HARPS-post, HARPS-pre, HARES-post, PFS-post, PFS-pre, UCLES	373	580	1992-12-16	2020-03-06	27.2	(15, 26, 19, 36)
HD 102870	β Vir (Zav-ijava)	6123	HARPS-pre, Hamilton, Levy, SOPHIE, Tull	346	276	1987-06-13	2019-05-01	31.9	(26, 16, 36, 7, 18)
HD 103095	CF UMa (Groom-bridge 1830)	5057	HARES-post, HARES-pre, Hamilton, Levy, SOPHIE	125	89	1999-01-21	2019-08-14	20.6	(19, 31, 7)
HD 109085	η Crv	6871	HARPS-pre	18	64	2006-03-12	2011-07-21	5.4	(26)
HD 109358	β CVn (Chara)	5878	HARES-post, HARES-pre, Levy, SOPHIE	247	254	2000-01-07	2022-02-08	22.1	(19, 31, 7)
HD 110897	10 CVn	5889	HARES-post, Levy, SOPHIE	303	222	2005-06-29	2020-03-09	14.7	(19, 31, 7)
HD 114613	GJ 9432	5688	CES-LC, CES-VLC, HARPS-post, HARPS-pre, HARES-post, PFS-post, PFS-pre, UCLES	534	905	1992-12-17	2021-05-26	28.4	(15, 26, 19, 36)
HD 114710	β Com	5996	Hamilton, SOPHIE	105	4	1987-06-13	2014-03-15	26.8	(16, 7)
HD 115404 A	GJ 505A	4843	ELODIE, HARES-post, HARES-pre, SOPHIE	95	63	1994-06-26	2023-05-16	28.9	(7, 31)
HD 115617	61 Vir	5552	HARPS-post, HARPS-pre, HARES-post, Hamilton, Levy, PFS-post, PFS-pre, UCLES	773	1329	1991-04-28	2021-08-06	30.3	(26, 19, 31, 36)
HD 122064	GJ 12002	4867	HARES-post, HARES-pre, Levy	281	231	2000-02-06	2020-03-09	20.1	(19, 31)
HD 125276 A	GJ 9476A	6120	HARPS-pre	16	58	2006-03-13	2014-05-17	8.2	(26)
HD 128167	σ Boo	6745	HARPS-pre, Hamilton	62	32	1988-03-04	2008-05-20	20.2	(26, 16)
HD 128620	α Cen A (Rigel Kentaurus)	5776	CES-LC, CHIRON, CTIO-ES	278	0	1993-03-08	2012-09-29	19.6	(2, 21)
HD 128621	α Cen B (Tollman)	5244	CES-LC, CHIRON, CTIO-ES, HARPS-post, HARPS-pre	632	1050	1993-03-08	2018-05-03	25.2	(2, 21, 26)

HD 131156 A	ξ Boo A	5487	HIRES-post, Hamilton, Levy, SOPHIE	244	44	1987-06-11	2020-04-16	32.8	(31, 7)
HD 131156 B	ξ Boo B	4288	Hamilton	11	0	1995-05-21	2008-07-02	13.1	(16)
HD 131977	KX Lib (GJ 570A)	4632	CES-LC, CES-VLC, HARPS-pre, Hamilton	149	87	1993-08-01	2009-03-02	15.6	(15, 26, 16)
HD 134083	45 Boo	6435	Hamilton, SOPHIE	56	11	1987-06-11	2011-04-19	23.9	(16, 7)
HD 136352	v2 Lup	5685	HARPS-post, HARPS-pre, HIRES-post, PFS-post, PFS-pre, UCLES	463	1149	1998-04-11	2020-03-15	21.9	(26, 19, 36)
HD 140538 A	ψ Ser A	5682	HARPS-post, HARPS-pre, HIRES-post, HIRES-pre, Levy	160	349	2002-02-02	2019-08-27	17.6	(26, 19, 31)
HD 140901 A	GJ 599A	5602	HARPS-pre, PFS-post, PFS-pre, UCLES	172	221	1998-04-11	2020-03-14	21.9	(26, 36)
HD 141004	λ Ser	5898	HIRES-post, HIRES-pre, Hamilton, Levy, SOPHIE	555	245	1987-09-09	2020-02-08	32.4	(19, 31, 7)
HD 142373	χ Her	5820	Hamilton	95	0	1987-09-10	2008-06-05	20.7	(16)
HD 142860	γ Ser	6285	Hamilton, SOPHIE	71	12	1987-06-11	2013-02-05	25.7	(16), 7
HD 143761	ρ CrB	5812	EXPRES, HIRES-post, HIRES-pre, Hamilton, Levy, SOPHIE	553	391	1997-04-25	2023-05-09	26.0	(37, 19, 31, 7)
HD 146233	18 Sco	5785	HARPS-post, HARPS-pre, HIRES-post, HIRES-pre, Levy, PFS-pre, SOPHIE, UCLES	452	1071	1996-07-19	2020-02-01	23.5	(26, 19, 31, 36, 7)
HD 147513	GJ 9559	5868	CORALIE-98, HARPS-post	75	184	1998-07-28	2021-09-10	23.1	(6, 26)
HD 149661	12 Oph	5262	HARPS-pre, HIRES-post, HIRES-pre, Hamilton, Levy, UCLES	182	115	1991-04-28	2020-02-01	28.8	(26, 19, 31, 36)
HD 156026	36 Oph C (Gumtibu C)	4476	HIRES-post, HIRES-pre, Levy, PFS-post, PFS-pre, UCLES	152	152	1998-06-19	2021-04-27	22.9	(19, 36)
HD 156274 A	41 Ara A	5235	CES-LC, CES-VLC, HARPS-pre	78	90	1993-03-08	2007-09-07	14.5	(15, 26)
HD 157214	72 Her	5704	HIRES-post, HIRES-pre, Hamilton, Levy	284	93	1987-06-11	2019-11-09	32.4	(19, 31)
HD 158633	GJ 675	5302	HIRES-post, Hamilton, Levy, SOPHIE	361	164	2001-07-22	2020-04-30	18.8	(19, 16, 31, 7)

HD 160691	μ Ara	5761	HARPS-post, PFS-post, UCLLES	353	754	1998-04-11	2019-07-19	21.3	(26, 36)
HD 165341	A 70 Oph A	5298	HIRES-post	5	8	2014-07-06	2018-07-02	4.0	(19)
HD 165499	ι Pav	5951	CORALIE-07, CORALIE-14, CORALIE-98	65	0	1999-03-22	2021-09-09	22.5	(35)
HD 166620	GJ 706	5028	HIRES-post, HAMILTON, Levy	352	131	1987-06-12	2020-03-08	32.7	(19, 31)
HD 168151	36 Dra	6473	SOPHIE	12	12	2007-08-25	2016-05-27	8.8	(7)
HD 182572	31 Aql	5593	ELODIE, HIRES-post, HIRES-pre, Levy	236	137	1994-04-24	2019-11-11	25.5	(7, 19, 31)
HD 185144	σ Dra (Al-safi)	5298	HIRES-post, HAMILTON, Levy, SOPHIE	1742	1477	1995-07-16	2020-05-30	24.9	(19, 31, 7)
HD 187013	17 Cyg A	6455	SOPHIE	15	15	2007-06-05	2016-05-27	9.0	(7)
HD 187691	A o Aql A	6134	HARPS-pre	12	48	2005-05-13	2006-07-20	1.2	(26)
HD 189567	GJ 776	5730	HARPS-post, HARPS-pre	260	1031	2003-10-25	2017-08-03	13.8	(26)
HD 190248	δ Pav	5576	HARPS-post, UCLLES	665	1652	1998-04-13	2016-10-01	18.5	(26, 36)
HD 190360	GJ 777A	5563	AFOE, ELODIE, HIRES-post, HIRES-pre, HAMILTON, Levy, NEID, SOPHIE	835	326	1994-09-15	2023-12-13	29.2	(4, 19, 31, 40, 7)
HD 191408	A GJ 783A	4980	CES-LC, CES-VLC, HARPS-pre, HIRES-post	115	179	1995-05-18	2019-11-10	24.5	(15, 26, 19)
HD 192310	GJ 785	5087	HARPS-post, HARPS-pre, HIRES-post, PFS-pre, UCLLES	768	2094	1998-11-03	2019-11-10	21.0	(26, 19, 36)
HD 193664	GJ 788	5930	ELODIE, SOPHIE	134	134	1994-09-15	2016-11-17	22.2	(7)
HD 197692	ψ Cap	6638	HARPS-pre	19	75	2004-05-31	2009-11-14	5.5	(26)
HD 199260	GJ 811	6270	HARPS-pre	13	52	2004-05-31	2011-06-14	7.0	(26)
HD 201091	61 Cyg A	4441	HIRES-post, HAMILTON, Levy	300	161	1987-06-11	2019-03-15	31.8	(19, 16, 31)
HD 201092	61 Cyg B	4107	HIRES-post, HAMILTON, Levy	296	178	1987-06-12	2019-12-27	32.5	(19, 31)
HD 202560	AX Mic (Lacaille 8760)	3874	HARPS-post, HIRES-post	93	354	2008-07-20	2021-12-25	13.4	(26, 19)
HD 203608	γ Pav	6095	HARPS-pre	19	71	2004-05-22	2009-11-14	5.5	(26)
HD 206860	HN Peg	5939	HAMILTON, Levy, SOPHIE	109	20	1987-09-09	2018-11-05	31.2	(16, 30, 7)

HD 207129	GJ 838	5935	CES-LC, CES-VLC, HARPS-post, HARPS-pre	179	616	1994-11-28	2021-09-14	26.8	(15, 26)
HD 209100	ϵ Ind	4641	CES-LC, CES-VLC, HARPS-post, HARPS-pre, UVES	266	785	1992-11-03	2021-12-29	29.2	(15, 26, 25)
HD 210302	τ PsA	6364	HARPS-pre, HIRES-post, HIRES-pre	88	239	1999-06-12	2019-06-16	20.0	(26, 19)
HD 212330 A	GJ 857A	5660	CORALIE-07, CORALIE-14, CORALIE-98	79	0	1999-06-24	2020-12-16	21.5	(35)
HD 213845 A	ν Aqr A	6605	HARPS-post, HARPS-pre	28	86	2005-08-20	2017-10-12	12.1	(26)
HD 215648 A	ξ Peg A	6193	Hamilton, SOPHIE	113	10	1987-09-08	2011-10-12	24.1	(16, 7)
HD 216803	TW PsA (Fomalhaut B)	4601	HARPS-pre, HIRES-post, HIRES-pre, UCLES	43	80	2002-05-28	2018-07-02	16.1	(26, 19, 36)
HD 217987	Lacaille 9352	3680	HARPS-post, HARPS-pre, HIRES-post, HIRES-pre	262	837	1998-06-19	2019-06-25	21.0	(26, 19)
HD 219134	GJ 892	4874	HARPS-North, HIRES-post, Hamilton, Levy	543	421	1992-10-11	2020-01-31	27.3	(17, 19, 31)
HD 219482	GJ 1282	6280	HARPS-pre	15	60	2005-08-20	2011-01-06	5.4	(26)
HD 219623	GJ 4324	6084	HIRES-post	36	60	2008-08-10	2020-02-01	11.5	(19)
HD 222368	ι Psc	6200	HARPS-pre, Hamilton, SO-PHIE	121	152	1987-09-08	2015-08-06	27.9	(26, 16, 7)

Note. Data have been binned to nightly intervals prior to counting. The stellar properties shown are taken from the SPORRES-HWO Catalog (Harada et al. 2024), which were inherited from the NASA ExEP Mission Star List (Mamajek and Stapelfeldt 2024).

[†] Stellar activity indicators (SAI).

References. (1) Butler et al. (1999); (2) Endl et al. (2001); (3) Naef et al. (2001); (4) Naef et al. (2003); (5) Naef et al. (2004); (6) Mayor et al. (2004); (7) Moutaka et al. (2004); (8) Benedict et al. (2006); (9) Butler et al. (2006); (10) Wittenmyer et al. (2007); (11) Wittenmyer et al. (2009); (12) McArthur et al. (2010); (13) Endl et al. (2012); (14) Marmier et al. (2013); (15) Zechmeister et al. (2013); (16) Fischer et al. (2014); (17) Motalleb et al. (2015); (18) Endl et al. (2016); (19) Butler et al. (2017); (20) Bourrier et al. (2018); (21) Zhao et al. (2018); (22) Díaz et al. (2019); (23) Boehle et al. (2019); (24) Brems et al. (2019); (25) Feng et al. (2019); (26) Trifonov et al. (2020); (27) Damasso et al. (2020); (28) Stock et al. (2020); (29) Cabot et al. (2021); (30) Hirsch et al. (2021); (31) Rosenthal et al. (2021); (32) Roettenbacher et al. (2022); (33) Zhao et al. (2022); (34) Subjak et al. (2023); (35) Barbato et al. (2023); (36) Lalouis et al. (2023); (37) Brewer et al. (2023); (38) Nari et al. (2025); (39) Gupta et al. (2025); (40) Giovannazzi et al. (2025a).

Table 4.A1: Summary of Target Star Observations.

Observatory	Instrument Name(s)	λ Range	Calib. [†]	Telescope	D (m)	Refs.
Calar Alto Observatory, Almería, Spain	CARMENES (Calar Alto high-Resolution search for M dwarfs with Exoearths with Near-infrared and optical Échelle Spectrographs)	0.52–1.71 μm	FP, ThNe, UAr, UNe	3.5 m Telescope	3.5	(13)
Cerro Tololo Inter-American Observatory (CTIO), Mt. Cerro Tololo, Coquimbo, Chile	CHIRON (CTIO High Resolution spectrometer) CTIO-ES (CTIO Échelle Spectrometer)	410–870 nm 401–730 nm	I ₂ , ThAr I ₂	Small and Moderate Aperture Research Telescope System (SMARTS) Small and Moderate Aperture Research Telescope System (SMARTS)	1.5 1.5	(14) (22)
Kitt Peak National Observatory (KPNO), Kitt Peak, Arizona, USA	NEID (NN-EXPLORE Exoplanet Investigations with Doppler Spectroscopy)	380–930 nm	FP, ThAr, LFC	Wisconsin-Indiana-Yale-NOIRLab (WIYN) 3.5 m Telescope	3.5	(18)
La Silla Observatory, Coquimbo, Chile	CES-LC (Coudé Échelle Spectrometer + Long Camera) CES-VLC (Coudé Échelle Spectrometer + Very Long Camera) CORALIE (CORALIE)	536.7–541.2 nm 537.6–541.2 nm 388–681 nm	I ₂ I ₂ ThAr	Coudé Auxiliary Telescope (CAT) ESO 3.6 m Telescope Leonhard Euler Swiss Telescope	1.4 3.6 1.2	(1) (1) (9)
Las Campanas Observatory (LCO), Atacama, Chile	HARPS (High Accuracy Radial Velocity Planet Searcher) PFS (Planet Finder Spectrograph)	378–691 nm 391–734 nm	ThAr I ₂ , ThAr	ESO 3.6 m Telescope Magellan II Telescope	3.6 6.5	(11) (15)
Lick Observatory, Mt. Hamilton, California, USA	Hamilton (Hamilton Échelle Spectrometer) Levy (Levy Spectrometer)	0.34–1.1 μm 374–970 nm	I ₂ I ₂ , ThArNe	C. Donald Shane Telescope Automated Planet Finder (APF)	3.0 2.4	(2) (17)
Lowell Observatory, Flagstaff, Arizona, USA	EXPRES (EXtreme PREcision Spectrograph)	380–780 nm	LFC, ThAr	Lowell Discovery Telescope (LDT)	4.3	(20)
McDonald Observatory, Texas, USA	HRS (High Resolution Spectrograph) Tull (Robert G. Tull Coudé Spectrograph)	0.42–1.1 μm 0.34–1.0 μm	I ₂ , ThAr I ₂	Hobby-Eberly Telescope (HET) Harlan J. Smith (HJS) Telescope	10.0 2.7	(8) (6)
Observatoire de Haute-Provence (OHP), Alpes-de-Haute-Provence, France	ELODIE (ELODIE) SOPHIE (Spectrographe pour l’Observation des Phénomènes des Intérieurs stellaires et des Exoplanètes)	390.6–681.1 nm 387.2–694.3 nm	FP, ThAr ThAr	1.93 m Telescope 1.93 m Telescope	1.93 1.93	(7) (12)

Observatorio del Roque de los Muchachos (ORM), La Palma, Canary Islands, Spain	HARPS-North (High Accuracy Radial velocity Planet Searcher for the Northern hemisphere)	383–693 nm	ThAr	Telescopio Nazionale Galileo (TNG)	3.58	(16)
Observatorio del Teide, Mt. Teide, Tenerife, Spain	SONG (Stellar Observations Network échelle spectrometer)	440–690 nm	I ₂ , ThAr	Hertzprung SONG Telescope	1.0	(19)
Paranal Observatory, Cerro Paranal, Atacama, Chile	ESPRESSO (Échelle Spectrograph for Rocky Exoplanets and Stable Spectroscopic Observations)	378.2–788.7 nm	FP, LFC, ThAr	ESO Very Large Telescope (VLT)	8.2	(21)
	UVES (Ultraviolet and Visual Échelle Spectrograph)	0.3–1.1 μ m	I ₂	ESO Very Large Telescope (VLT) UT2	8.2	(10)
Siding Spring Observatory, Mt. Woorat, New South Wales, Australia	UCLES (University College London Spectrograph)	0.3–1.1 μ m	ThUXe	Anglo-Australian Telescope (AAT)	3.9	(3)
W. M. Keck Observatory, Mauna Kea, Hawaii, USA	HIRES (High Resolution Échelle Spectrometer)	0.3–1.0 μ m	I ₂ , ThAr	Keck I Telescope	10.0	(5)
Whipple Observatory, Mt. Hopkins, Arizona, USA	AFOE (Advanced Fiber-Optic échelle spectrometer)	392–664 nm	I ₂ , ThAr	Tillinghast Telescope	1.5	(4)

[†] Wavelength calibration methods: Fabry–Pérot (FP); iodine (I₂); Laser Frequency Comb (LFC); thorium-argon (ThAr); thorium-argon-neon (ThArNe); thorium-neon (ThNe); thorium-uranium-xenon (ThUXe); uranium-thorium (UAR); uranium-neon (UNe).

References. (1) Enard (1982); (2) Vogt (1987); (3) Diego et al. (1990); (4) Brown et al. (1994); (5) Vogt et al. (1994); (6) Tull et al. (1995); (7) Baranne et al. (1996); (8) Tull (1998); (9) Queloz et al. (2000); (10) Dekker et al. (2000); (11) Mayor et al. (2003); (12) Perruchot et al. (2008); (13) Quirrenbach et al. (2010); (14) Schwab et al. (2010); (15) Crane et al. (2010); (16) Cosentino et al. (2012); (17) Vogt et al. (2014); (18) Schwab et al. (2016); (19) Grundahl et al. (2017); (20) Blackman et al. (2020); (21) Pepe et al. (2021); (22) <https://www.ctio.noirlab.edu/~atokovin/eche11e/FECH-overview.html>.

Table 4.A2: Observatories and Instrument Characteristics.

HD	BJD (d)	RV (m s ⁻¹)	σ_{RV} (m s ⁻¹)	S-ind	H-ind	EW _{Hα} (Å)	R'_{HK}	BIS (m s ⁻¹)	FWHM (m s ⁻¹)	Inst.	Bibcode
190360	2455486.88629	-0.98	1.27	0.1375	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455399.93205	-2.32	1.17	0.1364	0.0323	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455169.75811	-14.17	1.46	0.1484	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455170.69301	-16.84	1.10	0.1383	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455635.15512	-5.50	1.07	0.1346	0.0321	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455285.15477	-8.04	1.05	0.1338	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455313.13424	-2.61	1.19	0.1348	0.0321	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455313.13490	-2.59	1.21	0.1363	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455542.68811	-2.86	1.28	0.1313	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455542.68742	-3.02	1.16	0.1271	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455542.68671	-3.04	1.43	0.1290	0.0323	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455399.93134	-0.27	1.41	0.1300	0.0323	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455313.13557	-2.04	1.27	0.1337	0.0321	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455374.08205	-15.06	1.17	0.1472	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455522.68215	-7.28	1.17	0.1346	0.0321	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455522.68151	-2.70	1.17	0.1330	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455522.68087	-0.22	1.24	0.1336	0.0322	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455404.95851	-7.19	1.09	0.1412	0.0323	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455635.15582	-3.69	1.09	0.1288	0.0321	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
190360	2455399.93277	1.89	1.27	0.1372	0.0323	-1	-1	0	-1	HIRES-post	2017AJ....153..208B
:	:	:	:	:	:	:	:	:	:	:	:

Notes. Null stellar activity indicators are given as “-1” (or “0” in the case of BIS). Stellar activity uncertainties are also provided in the complete table.
(Only the first 20 rows of data are shown here to demonstrate form and content. A machine-readable version of the full table in Harada et al. (2025) is available at the publisher’s website.)

Table 4.A3: Sample (Unbinned) RV Data for HD 190360.

HD 95128	0.04	$358.3^{+1.1}_{-1.4}$	5084.26	$0.38^{+0.11}_{-0.11}$	$-0.64^{+0.36}_{-0.38}$	$3.31^{+0.52}_{-0.51}$	$35.2^{+5.4}_{-5.5}$	1.01 ± 0.019	-4.52	FA
HD 95735	b	12.9381 ± 0.0016	$7702.93^{+0.4}_{-0.4}$	$0.134^{+0.011}_{-0.011}$	$2.38^{+0.75}_{-0.75}$	$1.29^{+0.12}_{-0.12}$	$2.35^{+0.35}_{-0.34}$	$0.0767^{+0.004}_{-0.004}$	-15.2	KC (24)
HD 95735	c	$2801.0^{+88.0}_{-88.0}$	4423 ± 100	$0.09^{+0.083}_{-0.083}$	$2.8^{+1.2}_{-1.2}$	1.7 ± 0.19	$18.7^{+3.1}_{-3.1}$	$2.77^{+0.16}_{-0.16}$	-14.2	KC (24)
HD 95735	0.03	$55.324^{+0.074}_{-0.066}$	$5212.7^{+4.2}_{-4.2}$	$0.14^{+0.016}_{-0.016}$	$0.4^{+1.4}_{-1.4}$	0.79 ± 0.13	$2.29^{+0.47}_{-0.44}$	$0.202^{+0.011}_{-0.012}$	-4.01	SA-R (24)
HD 102870	0.01	$2167.0^{+49.0}_{-49.0}$	9612 ± 110	$0.306^{+0.017}_{-0.017}$	$0.69^{+0.35}_{-0.35}$	$7.43^{+0.88}_{-0.88}$	$177.0^{+20.0}_{-20.0}$	$3.66^{+0.081}_{-0.081}$	-8.38	FA
HD 114613	0.01	$3851.0^{+33.0}_{-33.0}$	3318^{+29}_{-29}	$0.806^{+0.046}_{-0.046}$	$2.19^{+0.24}_{-0.24}$	$3.83^{+0.42}_{-0.42}$	$68.0^{+10.0}_{-10.0}$	$5.33^{+0.13}_{-0.13}$	-16.0	SA (18)
HD 114613	0.02	$4814.0^{+380.0}_{-380.0}$	4667^{+81}_{-81}	$0.057^{+0.061}_{-0.061}$	$-3.3^{+1.3}_{-1.3}$	$5.25^{+0.43}_{-0.43}$	$170.0^{+18.0}_{-18.0}$	$6.2^{+0.31}_{-0.31}$	-13.5	SA (18)
HD 115617	b	$4.215011^{+0.008}_{-0.008}$	$5200.597^{+0.008}_{-0.008}$	$0.036^{+0.007}_{-0.007}$	$-0.9^{+1.9}_{-1.9}$	2.5 ± 0.1	$5.8^{+0.3}_{-0.3}$	$0.04931^{+0.00072}_{-0.00072}$	-42.1	KC (6)
HD 115617	c	$38.0864^{+0.082}_{-0.082}$	$5036.24^{+0.34}_{-0.34}$	$0.022^{+0.024}_{-0.024}$	$0.0^{+1.7}_{-1.7}$	3.64 ± 0.11	$17.84^{+0.7}_{-0.7}$	$0.2139^{+0.0031}_{-0.0031}$	-65.7	KC (6)
HD 115617	d	$123.15^{+0.15}_{-0.15}$	$5245.8^{+3.7}_{-3.7}$	$0.105^{+0.015}_{-0.015}$	$-1.35^{+0.69}_{-0.69}$	$1.52^{+0.14}_{-0.14}$	$10.92^{+1.0}_{-0.93}$	$0.4677^{+0.0068}_{-0.0068}$	-24.5	KC (6)
HD 115617	0.04	4026.3		—	—	—	—	—	-7.11	LPS
HD 128620	0.01	$333.9^{+1.3}_{-1.3}$	5062^{+21}_{-21}	$0.55^{+0.073}_{-0.073}$	$-1.19^{+0.19}_{-0.19}$	$7.49^{+0.38}_{-0.38}$	$72.3^{+6.4}_{-6.4}$	$0.975^{+0.023}_{-0.023}$	-19.5	FA
HD 128620	0.02	$62.34^{+0.13}_{-0.13}$	$5213.1^{+2.9}_{-3.0}$	0.22 ± 0.13	$-3.1^{+1.8}_{-1.0}$	3.51 ± 0.56	$22.4^{+3.6}_{-3.6}$	$0.319^{+0.075}_{-0.075}$	-5.33	FA
HD 128621	0.01	13560.3	—	—	—	—	—	—	-11.8	LPS
HD 136352	b	11.5766 ± 0.0017	$5204.65^{+0.26}_{-0.26}$	$0.057^{+0.061}_{-0.061}$	$2.8^{+1.8}_{-1.8}$	1.57 ± 0.11	$5.3^{+0.52}_{-0.52}$	$0.0981^{+0.003}_{-0.003}$	-22.0	KC (23)
HD 136352	c	27.581 ± 0.007	5284.51 ± 0.34	$0.044^{+0.037}_{-0.037}$	$1.28^{+0.81}_{-0.81}$	2.45 ± 0.12	$11.07^{+0.89}_{-0.89}$	$0.175^{+0.0082}_{-0.0082}$	-29.0	KC (23)
HD 136352	d	$107.49^{+0.14}_{-0.14}$	$5042.1^{+3.1}_{-3.1}$	$0.068^{+0.031}_{-0.031}$	$2.6^{+1.4}_{-1.4}$	1.53 ± 0.12	10.8 ± 1.1	$0.433^{+0.013}_{-0.013}$	-23.2	KC (23)
HD 140538 A	0.01	1449.0 ± 17.0	5722^{+26}_{-26}	$0.119^{+0.084}_{-0.084}$	$1.32^{+0.36}_{-0.36}$	$6.2^{+0.64}_{-0.64}$	$105.0^{+12.0}_{-11.0}$	$2.473^{+0.014}_{-0.014}$	-10.6	SA (30)
HD 141004	b	$15.5093^{+0.0015}_{-0.0015}$	$6719.83^{+0.33}_{-0.33}$	$0.139^{+0.011}_{-0.011}$	$0.09^{+0.81}_{-0.81}$	3.31 ± 0.36	$12.9^{+1.5}_{-1.4}$	0.1225 ± 0.0024	-12.4	KC (22)
HD 143761	b	39.84336 ± 0.00038	$7113.758^{+0.039}_{-0.039}$	$0.0385^{+0.0094}_{-0.0094}$	$-1.55^{+0.66}_{-0.66}$	67.07 ± 0.18	$393.0^{+2.0}_{-2.0}$	$0.2393^{+0.0064}_{-0.0064}$	-99.9	KC (28)
HD 143761	c	102.579 ± 0.041	$5204.4^{+2.1}_{-2.1}$	$0.077^{+0.053}_{-0.053}$	$-0.06^{+0.62}_{-0.62}$	3.94 ± 0.18	31.5 ± 2.2	$0.449^{+0.011}_{-0.011}$	-53.3	KC (28)
HD 143761	d	$267.8^{+1.8}_{-1.8}$	5250^{+20}_{-20}	$0.16^{+0.11}_{-0.11}$	$-1.0^{+0.31}_{-0.31}$	1.3 ± 0.2	$13.5^{+2.3}_{-2.3}$	$0.852^{+0.013}_{-0.013}$	-4.77	KC (28)
HD 146233	0.01	$2435.0^{+31.0}_{-31.0}$	7441 ± 110	$0.233^{+0.068}_{-0.068}$	$-1.73^{+0.43}_{-0.43}$	$3.7^{+0.31}_{-0.31}$	$79.0^{+7.0}_{-6.7}$	$3.624^{+0.073}_{-0.073}$	-21.6	SA (10)
HD 158633	0.01	$366.5^{+1.6}_{-1.6}$	11119 ± 18	$0.087^{+0.06}_{-0.06}$	$0.0^{+1.4}_{-1.4}$	$2.82^{+0.29}_{-0.29}$	$27.1^{+3.3}_{-3.3}$	$0.934^{+0.032}_{-0.032}$	-14.6	FA
HD 160691	b	644.93 ± 0.27	$3765.6^{+2.3}_{-2.3}$	$0.0505^{+0.0094}_{-0.0094}$	$0.41^{+0.17}_{-0.17}$	35.7 ± 0.2	556.0 ± 21.0	$1.57^{+0.029}_{-0.029}$	-82.5	KC (4)
HD 160691	c	4241.0^{+1600}_{-1600}	3237^{+24}_{-24}	0.039 ± 0.011	$1.96^{+0.34}_{-0.34}$	$24.6^{+1.1}_{-1.1}$	$719.0^{+63.0}_{-48.0}$	$5.52^{+0.03}_{-0.03}$	-58.7	KC (4)
HD 160691	d	9.63923 ± 0.00082	$5205.15^{+0.27}_{-0.27}$	$0.141^{+0.066}_{-0.066}$	$-2.65^{+0.58}_{-0.58}$	2.77 ± 0.19	$10.49^{+0.83}_{-0.83}$	0.0952 ± 0.0018	-25.3	KC (4)
HD 160691	e	308.54 ± 0.22	$4483.8^{+1.8}_{-1.8}$	0.075 ± 0.015	$-2.72^{+0.31}_{-0.31}$	12.89 ± 0.32	$156.6^{+7.0}_{-7.0}$	0.96 ± 0.018	-99.9	KC (4)
HD 165499	B	$8296.0^{+28.0}_{-28.0}$	$6184.4^{+9.2}_{-9.2}$	0.4342 ± 0.0016	$-2.7193^{+0.0093}_{-0.0093}$	$1354.3^{+3.7}_{-3.6}$	$444.9^{+4800.0}_{-4800.0}$	$8.6^{+0.43}_{-0.43}$	-45.6	KC-S (27)
HD 185144	0.01	2338.0 ± 34.0	6955^{+48}_{-48}	$0.214^{+0.064}_{-0.064}$	$2.37^{+0.30}_{-0.30}$	2.04 ± 0.13	33.7 ± 2.4	$3.119^{+0.064}_{-0.064}$	-29.1	SA (30)
HD 185144	0.02	$363.34^{+0.69}_{-0.69}$	$5365.7^{+6.6}_{-6.6}$	$0.502^{+0.069}_{-0.069}$	2.65 ± 0.17	$2.01^{+0.2}_{-0.2}$	$15.9^{+1.4}_{-1.4}$	$0.901^{+0.016}_{-0.016}$	-25.3	FA
HD 185144	0.03	121.55 ± 0.22	$5189.8^{+5.6}_{-5.6}$	$0.093^{+0.064}_{-0.064}$	$-2.7^{+1.6}_{-1.6}$	$1.45^{+0.21}_{-0.21}$	$9.1^{+1.4}_{-1.4}$	$0.4344^{+0.0077}_{-0.0077}$	-7.54	FA
HD 189567	b	$14.2857^{+0.0032}_{-0.0032}$	$5477.54^{+0.42}_{-0.42}$	$0.091^{+0.082}_{-0.082}$	2.5 ± 1.1	2.58 ± 0.21	$9.87^{+0.96}_{-0.95}$	$0.1164^{+0.0029}_{-0.0029}$	-18.7	KC (20)
HD 189567	c	$33.571^{+0.039}_{-0.039}$	5187.3 ± 1.7	$0.14^{+0.12}_{-0.12}$	$-0.6^{+2.5}_{-1.5}$	$1.6^{+0.23}_{-0.24}$	8.0 ± 1.2	$0.2057^{+0.0053}_{-0.0053}$	-5.65	KC (20)
HD 190360	b	2886.4 ± 3.9	6762.4 ± 6.9	$0.3153^{+0.0071}_{-0.0071}$	0.25 ± 0.026	22.11 ± 0.26	476.0 ± 16.0	$4.009^{+0.064}_{-0.064}$	-99.9	KC (5)
HD 190360	c	$17.11695^{+0.0005}_{-0.0005}$	5198.61 ± 0.19	0.148 ± 0.024	-0.83 ± 0.18	5.43 ± 0.14	22.0 ± 0.9	$0.1313^{+0.0021}_{-0.0021}$	-99.9	KC (5)
HD 190360	0.03	$88.662^{+0.063}_{-0.063}$	$5204.5^{+3.7}_{-3.7}$	$0.124^{+0.015}_{-0.015}$	$0.22^{+0.83}_{-0.83}$	1.4 ± 0.15	10.0 ± 1.0	$0.393^{+0.0062}_{-0.0062}$	-13.6	PC
HD 192310	b	74.262 ± 0.032	$5767.85^{+0.68}_{-0.68}$	$0.03^{+0.03}_{-0.03}$	$-0.2^{+1.7}_{-1.7}$	$2.541^{+0.098}_{-0.097}$	$13.64^{+0.73}_{-0.71}$	$0.3127^{+0.0053}_{-0.0053}$	-37.2	KC (9)
HD 192310	c	546.5 ± 3.4	5256^{+12}_{-12}	$0.053^{+0.081}_{-0.081}$	$-2.9^{+1.8}_{-1.8}$	1.38 ± 0.11	14.3 ± 1.2	1.183 ± 0.022	-33.7	KC (9)
HD 192310	0.03	$5650.0^{+4000.0}_{-4000.0}$	4165^{+240}_{-240}	$0.3^{+0.11}_{-0.11}$	$-2.72^{+0.55}_{-0.55}$	$2.17^{+0.99}_{-0.99}$	$47.0^{+31.0}_{-17.0}$	$5.6^{+2.4}_{-2.4}$	-17.2	SA (10)
HD 192310	0.04	$43.623^{+0.024}_{-0.024}$	$5187.93^{+0.93}_{-0.93}$	$0.505^{+0.016}_{-0.016}$	$0.44^{+0.29}_{-0.29}$	$0.89^{+0.12}_{-0.12}$	3.45 ± 0.43	$0.2194^{+0.0039}_{-0.0039}$	-7.58	SA-R (10)
HD 192310	0.05	$39.44^{+0.05}_{-0.05}$	$5195.0^{+1.7}_{-1.7}$	$0.18^{+0.12}_{-0.12}$	$-0.29^{+0.61}_{-0.61}$	1.0 ± 0.1	$4.11^{+0.45}_{-0.44}$	$0.2051^{+0.0086}_{-0.0086}$	-4.94	SA-R (10)
HD 192310	0.06	$24.567^{+0.03}_{-0.03}$	$5191.3^{+1.8}_{-1.8}$	$0.136^{+0.011}_{-0.011}$	3.0 ± 1.5	$0.632^{+0.1}_{-0.1}$	$2.3^{+0.34}_{-0.37}$	$0.1496^{+0.0038}_{-0.0038}$	-3.47	PC
HD 201091	0.01	$6918.0^{+32.0}_{-32.0}$	11195^{+800}_{-800}	$0.809^{+0.084}_{-0.084}$	$-1.78^{+0.23}_{-0.23}$	$11.7^{+2.2}_{-2.2}$	$127.0^{+17.0}_{-15.0}$	$5.56^{+0.19}_{-0.19}$	-8.03	FA
HD 201092	0.01	49.012 ± 0.029	6650.1^{+1400}_{-1400}	$0.141^{+0.099}_{-0.099}$	$0.37^{+0.77}_{-0.77}$	$1.88^{+0.24}_{-0.24}$	$4.99^{+0.94}_{-0.94}$	$0.181^{+0.012}_{-0.012}$	-7.39	SA-R (22)
HD 207129	0.01	$1393.0^{+12.0}_{-12.0}$	3867^{+61}_{-61}	0.19 ± 0.11	$-1.72^{+0.65}_{-0.65}$	$3.64^{+0.46}_{-0.46}$	$62.8^{+8.7}_{-8.3}$	$2.457^{+0.065}_{-0.065}$	-7.98	SA (10)
HD 210302	0.01	$115.52^{+0.27}_{-0.27}$	4176 ± 13	$0.41^{+0.13}_{-0.13}$	$-2.01^{+0.7}_{-0.7}$	$8.3^{+1.4}_{-1.4}$	$63.0^{+3.9}_{-3.9}$	$0.486^{+0.018}_{-0.018}$	-3.33	SRC
HD 212330 A	B	$14034.0^{+1800.0}_{-1800.0}$	11225^{+760}_{-760}	$0.1^{+0.03}_{-0.03}$	$-2.83^{+0.12}_{-0.12}$	$3993.0^{+2000.0}_{-1000.0}$	$256861.0^{+210000.0}_{-88000.0}$	$15.0^{+2.1}_{-2.1}$	-74.2	KC-S (27)
HD 217987	b	$9.26177^{+0.0083}_{-0.0083}$	$5197.14^{+0.28}_{-0.28}$	$0.083^{+0.058}_{-0.058}$	$0.1^{+0.3}_{-0.3}$	$2.81^{+0.37}_{-0.37}$	$6.9^{+2.2}_{-2.2}$	$0.0751^{+0.0095}_{-0.0095}$	-7.64	KC (19)
HD 217987	c	$21.7952^{+0.0023}_{-0.0023}$	$6177.42^{+0.61}_{-0.61}$	$0.265^{+0.076}_{-0.076}$	$-0.04^{+0.4}_{-0.4}$	$3.26^{+0.31}_{-0.31}$	$10.2^{+3.0}_{-3.0}$	$0.133^{+0.017}_{-0.017}$	-4.22	KC (19)
HD 217987	0.03	$39.223^{+0.024}_{-0.024}$	5190.8 ± 1.1	$0.29^{+0.15}_{-0.15}$	$2.02^{+0.44}_{-0.44}$	$2.28^{+0.32}_{-0.32}$	$8.5^{+2.7}_{-2.8}$	$0.197^{+0.033}_{-0.033}$	-5.62	SRC
HD 219134	b	$3.092926^{+6.8e-05}_{-6.7e-05}$	$5199.71^{+0.074}_{-0.074}$	$0.121^{+0.084}_{-0.084}$	$0.88^{+0.62}_{-0.62}$	2.12 ± 0.16	$3.73^{+0.34}_{-0.33}$	$0.03671^{+0.00086}_{-0.00091}$	-12.8	KC (13)

HD 219134	c	$6.76379^{+0.00059}_{-0.00057}$	$5200.97^{+0.32}_{-0.37}$	$0.18^{+0.13}_{-0.048}$	$0.14^{+0.85}_{-0.4^{+1.2}_{-1.0}}$	$1.39^{+0.18}_{-0.17}$	$3.12^{+0.42}_{-0.4^{+1.1}_{-1.0}}$	0.0618 ± 0.0015	-7.63	KC (13)
HD 219134	d	$46.743^{+0.0098}_{-0.0099}$	$5207.93^{+0.85}_{-0.86}$	$0.048^{+0.044}_{-0.063}$	$-0.4^{+1.2}_{-2.1}$	3.53 ± 0.17	$15.5^{+1.1}_{-1.0}$	$0.2244^{+0.0053}_{-0.0055}$	-38.4	KC (13)
HD 219134	f	$22.7931^{+0.0049}_{-0.0049}$	$5210.72^{+0.66}_{-0.67}$	$0.063^{+0.069}_{-0.069}$	$0.0^{+2.1}_{-0.6}$	1.87 ± 0.16	$6.43^{+0.66}_{-0.64}$	$0.139^{+0.0033}_{-0.0033}$	-12.8	KC (13)
HD 219134	h	2090.0 ± 14.0	6803^{+22}_{-21}	0.05 ± 0.03	$2.6^{+0.67}_{-0.61}$	5.7 ± 0.2	$88.0^{+5.4}_{-5.3}$	$2.828^{+0.068}_{-0.071}$	-54.3	KC (13)
HD 219134	0.04	$192.32^{+0.45}_{-0.39}$	$5167.8^{+6.5}_{-6.1}$	$0.07^{+0.049}_{-0.049}$	$2.9^{+1.5}_{-1.5}$	2.03 ± 0.17	14.2 ± 1.4	0.576 ± 0.014	-10.6	PC
HD 219134	0.07	19241.3							-4.08	LPS
HD 219134	0.08	$43.475^{+0.024}_{-0.026}$	$5193.1^{+3.2}_{-2.6}$	$0.37^{+0.15}_{-0.14}$	$-0.15^{+0.48}_{-0.4}$	$1.17^{+0.21}_{-0.19}$	$4.61^{+0.74}_{-0.72}$	$0.2138^{+0.005}_{-0.0053}$	-3.15	SA-R (12)
HD 219623	0.01	$48.481^{+0.038}_{-0.038}$	$6843.6^{+2.1}_{-2.6}$	$0.21^{+0.14}_{-0.14}$	$-1.12^{+0.78}_{-0.65}$	9.4 ± 1.3	$49.3^{+7.5}_{-7.3}$	$0.255^{+0.0062}_{-0.0065}$	-3.69	PC

† False alarm (FA); known companion (KC; -S indicates stellar); planet candidate (PC); stellar activity (SA; -R indicates rotation); long period signal (LPS); source requiring confirmation (SRC).

References. (1) Balunas et al. (1995); (2) Butler et al. (2001); (3) Lovis et al. (2006); (4) Pepe et al. (2007); (5) Wright et al. (2009); (6) Vogt et al. (2010); (7) Gregory and Fischer (2010); (8) Curiel et al. (2011); (9) Pepe et al. (2011); (10) Lovis et al. (2011); (11) Marmier et al. (2013); (12) Motaiebi et al. (2015); (13) Vogt et al. (2015); (14) Baluev (2015); (15) Bourrier et al. (2018); (16) Garg et al. (2019); (17) Wittenmyer et al. (2019); (18) Luhn et al. (2020); (19) Jeffers et al. (2020); (20) Unger et al. (2021); (21) Llop-Sayson et al. (2021); (22) Rosenthal et al. (2021); (23) Delrez et al. (2021); (24) Hurt et al. (2022); (25) Hatzes et al. (2022); (26) Šubjak et al. (2023); (27) Barbato et al. (2023); (28) Brewer et al. (2023); (29) Burrows et al. (2024); (30) Isaacson et al. (2024).

(This table is available in its entirety in machine-readable form in Harada et al. (2025) at the publisher's website.)

Table 4.A4: RV Signals Identified by RVSearch.

HD Name	$\dot{\gamma}$ ($\text{m s}^{-1} \text{d}^{-1}$)	$\ddot{\gamma}$ ($\text{m s}^{-1} \text{d}^{-2}$)
HD 2151	0.00076 ± 0.00022	—
HD 4614 A	0.01689 ± 0.00033	—
HD 16895 A	$-0.0055^{+0.0009}_{-0.00092}$	—
HD 19373	$-0.00073^{+0.00017}_{-0.00016}$	—
HD 20010 A	-0.0303 ± 0.0015	—
HD 20630	-0.0057 ± 0.0016	—
HD 20766	$-0.00244^{+0.00066}_{-0.00067}$	—
HD 20807	$-0.00057^{+0.00019}_{-0.0002}$	—
HD 26965 A	0.00035 ± 0.00011	—
HD 30652	0.0063 ± 0.0051	$-1.18e-05 \pm 3.1e-06$
HD 32147	$0.00021^{+0.00011}_{-0.0001}$	—
HD 32923	$0.00495^{+0.00028}_{-0.00029}$	—
HD 39091	$-8e-05 \pm 0.00021$	—
HD 46588 A	$0.0157^{+0.0064}_{-0.0067}$	—
HD 65907 A	$-0.00094^{+9.1e-05}_{-9.3e-05}$	—
HD 76151	$-0.00144^{+0.00082}_{-0.00086}$	—
HD 90839	-0.0001 ± 0.0014	$8.3e-07 \pm 2.2e-07$
HD 100623 A	0.0051 ± 0.0002	—
HD 101501	$-0.00161^{+0.00057}_{-0.00058}$	$-6.6e-07 \pm 1.2e-07$
HD 102870	$-0.00129^{+0.00029}_{-0.0003}$	—
HD 103095	$0.0271^{+0.0024}_{-0.0027}$	—
HD 114613	$-0.00177^{+0.00028}_{-0.0002}$	—
HD 115404 A	$0.01474^{+0.00089}_{-0.0009}$	—
HD 122064	-0.0008 ± 0.00016	—
HD 128620	0.3513 ± 0.0021	$1.193e-05^{+3.7e-07}_{-3.8e-07}$
HD 128621	$-0.502^{+0.023}_{-0.034}$	$-2.44e-05^{+5.4e-06}_{-5.6e-06}$
HD 131156 A	0.067 ± 0.002	$2.2e-06 \pm 3e-07$
HD 131977	-0.01182 ± 0.00058	—
HD 136352	-0.00023 ± 0.00011	—
HD 140538 A	$-0.00519^{+0.0003}_{-0.00031}$	$-1.03e-06 \pm 2.1e-07$
HD 140901 A	0.0029 ± 0.0008	—
HD 142373	-0.00025 ± 0.00053	$-1.11e-06^{+2.7e-07}_{-2.6e-07}$
HD 146233	-0.00169 ± 0.00019	—
HD 147513	0.0056 ± 0.0037	$3.3e-06 \pm 5e-07$
HD 156274 A	$0.025^{+0.00072}_{-0.00069}$	—
HD 160691	-0.00054 ± 0.00013	$-9.8e-07^{+5.1e-07}_{-7e-07}$
HD 189567	$0.00021^{+0.00022}_{-0.00023}$	$7.4e-07^{+1.4e-07}_{-1.5e-07}$
HD 190248	$-0.000515 \pm 7.6e-05$	—
HD 190360	$-0.00027^{+0.00014}_{-0.00013}$	—
HD 191408 A	$0.0082^{+0.00024}_{-0.00023}$	—
HD 192310	$0.0001^{+0.00014}_{-0.00013}$	$-2.8e-07^{+2.4e-07}_{-1.9e-07}$
HD 201091	$-0.0061^{+0.00043}_{-0.00052}$	—
HD 201092	$0.01298^{+0.00039}_{-0.00038}$	$-3.91e-07 \pm 5.9e-08$
HD 207129	-0.00049 ± 0.00034	—
HD 209100	0.00569 ± 0.00026	$-8.2e-07^{+5.4e-08}_{-5.5e-08}$
HD 212330 A	$0.07^{+0.2}_{-0.28}$	$0.000145^{+0.00011}_{-5.3e-05}$
HD 219134	$0.0078^{+0.0047}_{-0.004}$	$-5.6e-07^{+3.1e-07}_{-3.3e-07}$
HD 222368	$0.00067^{+0.00076}_{-0.00075}$	$6e-07 \pm 1.8e-07$

(This table is available in its entirety in machine-readable form in Harada et al. (2024) at the publisher's website.)

Table 4.A5: Long-term Trends Signals Identified by RVSearch.

HD Name	Planet	Det. Method [†]	Discovery Year	P (yr)	e	$M_p \sin i$ (M_J)	a (au)	Refs.	Notes
HD 10700 (τ Cet)	e	RV	2017	162.87	0.18	3.93	0.538	(3)	Disputed planet candidate.
	f	RV	2017	636.13	0.16	3.93	1.334	(3)	Disputed planet candidate.
	g	RV	2017	20.0	0.06	1.75	0.133	(3)	Disputed planet candidate.
	h	RV	2017	49.41	0.23	1.83	0.243	(3)	Disputed planet candidate.
HD 20794 (82 Eri)	e	RV	2017	147.02	0.29	4.77	0.509	(2)	Disputed planet candidate.
	f	RV	2025	647.6	0.45	5.82	1.3541	(11)	RV precision limited by possible unmodeled instrumental drift in the ESPRESSO data.
HD 33564	b	RV	2005	388.0	0.34	2892.1	1.1	(5)	Original ELODIE data used for discovery are not public.
HD 86728 A (20 LMi A)	b	RV	2025	31.1515	0.067	9.43	0.1916	(7)	Signal was detected but did not meet the FAP=0.01 significance cutoff.
HD 95128 (47 UMa)	d	RV	2009	14002.0	0.16	521.22	11.6	(6)	Long-period signal consistent with this planet's period was detected, but the full orbit could not be sampled.
HD 102365	b	RV	2010	122.1	0.34	16.0	0.46	(13)	Signal only appears in the UCLES data.
HD 115404 A	b	RV, Astr	2022	10.49488	0.232	30.82936	0.088	(4)	Disputed; original study does not detail the analysis of this system.
	c	RV, Astr	2022	15319.23	0.211	3279.671	11.364	(4)	Disputed; original study does not detail the analysis of this system.
HD 140901 A	b	RV, Astr	2022	9.02378	0.472	15.57359	0.085	(4)	Disputed planet candidate.
	c	RV, Astr	2022	14386.0	0.77	572.0911	11.8	(12)	No significant signals identified using RV alone without astrometry.
HD 143761 (ρ CrB)	e	RV	2023	12.949	0.126	3.79	0.1061	(1)	Signal was detected but did not meet the FAP=0.01 significance cutoff.
HD 147513	b	RV	2003	528.4	0.26	385.0	1.32	(10)	Signal does not meet the FAP=0.01 significance cutoff when HARPS data are included with the original CORALIE data.
HD 206860 (HN Peg)	b	Im	2006	—	—	6991.57	773.0	(8)	Directly imaged planet; RVs are not sensitive in this regime.
HD 209100 (eps Ind)	b	RV, Astr, Im	2019	—	0.4	2005.497	28.4	(9)	Signal appears as a long-term trend in the RV data without constraints from astrometry or imaging.
HD 219134	g	RV	2015	94.2	0.0	10.80622	0.3753	(14)	Disputed planet candidate.

[†] Detection method: Radial velocity (RV); astrometry (Astr); imaging (Im).

References. (1) Brewer et al. (2023); (2) Feng et al. (2017a); (3) Feng et al. (2017b); (4) Feng et al. (2022); (5) Galland et al. (2005); (6) Gregory and Fischer (2010); (7) Gupta et al. (2025); (8) Luhman et al. (2007); (9) Matthews et al. (2024); (10) Mayor et al. (2004); (11) Nari et al. (2025); (12) Philipot et al. (2023); (13) Tinney et al. (2011); (14) Vogt et al. (2015).

Table 4.A6: Previously Reported Planets Not Detected in this Work.

HD Name	T_{eff} (K)	IHZ (Inner Edge of the HZ)				MHZ (Middle of the HZ)				OHZ (Outer Edge of the HZ)			
		a_{HZ} (au)	P_{HZ} (yr)	$M_p \sin i$ (M_J)	K_{RV} (m s^{-1})	a_{MHZ} (au)	P_{MHZ} (yr)	$M_p \sin i$ (M_J)	K_{RV} (m s^{-1})	a_{OHZ} (au)	P_{OHZ} (yr)	$M_p \sin i$ (M_J)	K_{RV} (m s^{-1})
HD 166	5491	0.81	0.75	246.7 [41.49]	24.1 [39.3]	0.99	1.01	274.4 [470.5]	24.3 [40.1]	1.39	1.70	324.8 [563.7]	24.2 [41.0]
HD 1581	5932	1.11	1.11	10.7 [22.5]	0.8 [1.7]	1.35	1.49	11.9 [24.0]	0.8 [1.7]	1.87	2.43	13.5 [26.2]	0.8 [1.7]
HD 2151	5806	1.85	2.42	59.0 [110.1]	3.5 [6.0]	2.26	3.26	67.5 [138.3]	3.7 [6.6]	3.14	5.37	91.2 [226.3]	4.3 [9.1]
HD 3651 A	5203	0.74	0.69	15.0 [31.6]	1.7 [3.2]	0.91	0.94	17.2 [34.6]	1.7 [3.2]	1.29	1.59	20.8 [39.4]	1.7 [3.2]
HD 4391	5887	0.95	0.94	315.4 [556.7]	24.5 [41.3]	1.16	1.26	352.1 [620.8]	24.9 [42.2]	1.61	2.06	431.6 [857.0]	26.0 [45.2]
HD 4614 A	5907	1.11	1.09	25.8 [69.3]	2.1 [4.8]	1.35	1.46	30.7 [93.2]	2.3 [5.7]	1.87	2.39	41.5 [150.8]	2.6 [8.3]
HD 4628	5007	0.56	0.48	11.4 [22.4]	1.5 [2.7]	0.69	0.65	13.5 [27.3]	1.6 [2.9]	0.99	1.11	18.4 [36.1]	1.8 [3.2]
HD 7570	6110	1.39	1.53	90.7 [166.3]	6.2 [10.2]	1.68	2.05	102.7 [193.6]	6.4 [10.3]	2.33	3.32	128.3 [247.0]	6.8 [11.0]
HD 9826 A	6154	1.79	2.21	73.3 [185.5]	4.0 [11.1]	2.17	2.95	79.8 [166.5]	4.0 [8.7]	3.00	4.78	91.8 [186.3]	4.0 [7.7]
HD 10476	5204	0.68	0.61	20.9 [43.0]	2.5 [4.7]	0.84	0.83	23.5 [48.2]	2.5 [4.8]	1.20	1.42	28.4 [56.9]	2.6 [4.8]
HD 10647	6155	1.22	1.26	103.5 [222.5]	7.7 [16.2]	1.48	1.68	116.9 [246.6]	7.9 [17.2]	2.04	2.73	146.5 [321.0]	8.4 [18.6]
HD 10700	5356	0.72	0.63	44.9 [9.5]	0.5 [1.0]	0.88	0.85	5.1 [11.0]	0.5 [1.1]	1.25	1.43	6.5 [13.9]	0.6 [1.1]
HD 10780	5358	0.73	0.65	34.9 [61.8]	4.1 [7.0]	0.89	0.88	40.0 [69.4]	4.2 [7.2]	1.26	1.49	50.3 [89.2]	4.4 [7.5]
HD 14412	5401	0.67	0.57	13.5 [28.8]	1.6 [3.1]	0.82	0.77	15.2 [32.5]	1.6 [3.2]	1.16	1.30	18.2 [37.8]	1.6 [3.2]
HD 16895 A	6263	1.46	1.60	434.4 [796.7]	26.5 [45.9]	1.77	2.14	485.3 [872.4]	27.0 [45.6]	2.43	3.45	579.9 [1038.6]	27.9 [45.8]
HD 17051	6157	1.29	1.37	214.9 [512.3]	14.4 [32.4]	1.57	1.83	242.5 [565.2]	14.8 [32.6]	2.16	2.97	300.6 [660.1]	15.8 [33.0]
HD 17925	5199	0.64	0.57	730.3 [1334.7]	89.6 [150.2]	0.79	0.78	814.6 [1454.6]	91.3 [152.8]	1.12	1.32	973.3 [1815.6]	94.5 [162.2]
HD 19373	5952	1.47	1.72	41.8 [81.6]	2.9 [5.3]	1.79	2.31	46.0 [89.0]	2.9 [5.3]	2.49	3.77	55.2 [106.7]	2.9 [5.5]
HD 20010 A	6195	2.01	2.56	157.5 [452.2]	9.6 [24.2]	2.44	3.42	199.0 [604.3]	10.9 [28.7]	3.36	5.52	333.2 [1122.3]	15.4 [46.9]
HD 20630	5709	0.92	0.89	512.0 [921.5]	45.5 [79.0]	1.12	1.20	559.9 [1040.5]	45.4 [79.7]	1.57	1.99	666.2 [1269.2]	45.6 [80.9]
HD 20766	5710	0.89	0.83	132.3 [247.5]	12.8 [22.3]	1.08	1.12	149.4 [279.3]	13.0 [22.9]	1.51	1.85	187.5 [349.0]	13.7 [24.3]
HD 20794	5432	0.81	0.75	6.1 [13.5]	0.6 [1.3]	1.00	1.01	7.2 [16.0]	0.7 [1.4]	1.41	1.70	9.1 [20.9]	0.7 [1.5]
HD 20807	5847	1.00	0.96	21.5 [42.4]	1.9 [3.5]	1.22	1.30	24.5 [50.0]	2.0 [3.7]	1.69	2.13	30.6 [64.8]	2.2 [4.1]
HD 22049	5098	0.59	0.52	26.3 [49.0]	3.7 [6.1]	0.73	0.70	30.1 [58.9]	3.8 [6.5]	1.04	1.20	39.3 [92.5]	4.2 [8.2]
HD 22484	5996	1.72	2.12	129.7 [282.5]	8.3 [15.6]	2.10	2.84	154.3 [372.3]	9.0 [18.4]	2.90	4.64	233.9 [500]	11.4 [30]
HD 23249	5045	1.75	2.49	27.9 [64.0]	1.8 [3.9]	2.16	3.39	32.4 [74.2]	1.8 [4.0]	3.09	5.81	41.6 [90.4]	1.9 [4.1]
HD 25457	6268	1.39	1.48	1496.7 [2577.5]	104.5 [182.2]	1.68	1.98	1694.6 [2989.3]	106.8 [184.6]	2.31	3.19	2070.4 [3830.5]	111.7 [190.8]
HD 25998	6381	1.47	1.64	1802.5 [3357.2]	83.2 [143.2]	1.78	2.19	1998.8 [3661.4]	84.0 [143.5]	2.44	3.51	2373.2 [4392.6]	87.1 [146.0]
HD 26965 A	5133	0.65	0.57	12.7 [25.2]	1.5 [2.8]	0.80	0.77	14.1 [27.8]	1.5 [2.9]	1.14	1.32	16.2 [32.5]	1.5 [2.9]
HD 30495	5843	0.97	0.94	272.5 [535.8]	25.0 [44.1]	1.19	1.27	304.4 [601.1]	25.2 [44.4]	1.65	2.08	368.5 [751.1]	25.9 [45.6]
HD 30652	6443	1.59	1.80	785.1 [1625.5]	51.7 [98.3]	1.93	2.39	875.3 [1856.5]	53.4 [101.6]	2.64	3.83	1150.4 [2524.2]	59.2 [114.8]
HD 32147	4810	0.56	0.48	7.5 [16.4]	1.2 [2.3]	0.68	0.65	8.4 [18.8]	1.2 [2.4]	0.99	1.14	10.3 [22.5]	1.2 [2.5]
HD 32923	5691	1.54	1.88	34.2 [68.4]	2.4 [4.4]	1.88	2.54	37.0 [77.0]	2.3 [4.4]	2.64	4.20	43.7 [94.7]	2.4 [4.8]
HD 34411	5854	1.30	1.43	21.1 [43.9]	1.6 [3.2]	1.59	1.92	23.7 [51.1]	1.6 [3.4]	2.21	3.16	29.0 [67.0]	1.7 [3.6]
HD 37394	5226	0.70	0.63	214.5 [385.5]	25.3 [41.8]	0.86	0.85	235.6 [437.3]	25.3 [42.0]	1.22	1.44	285.3 [543.1]	25.4 [42.8]
HD 38392	4950	0.54	0.44	210.3 [413.3]	39.5 [69.2]	0.67	0.61	238.8 [477.8]	40.5 [72.1]	0.96	1.04	304.1 [569.1]	42.7 [75.7]
HD 38858	5731	0.90	0.85	28.3 [67.8]	2.8 [6.1]	1.10	1.15	32.1 [77.0]	2.8 [6.3]	1.54	1.90	39.6 [94.2]	3.0 [6.6]
HD 39091	5982	1.22	1.30	32.0 [118.3]	2.3 [8.5]	1.48	1.74	35.7 [129.9]	2.4 [8.7]	2.06	2.84	42.2 [141.5]	2.4 [8.3]
HD 43042	6539	1.65	1.87	356.0 [746.7]	21.4 [43.6]	2.00	2.49	398.0 [823.9]	22.1 [43.4]	2.72	3.96	490.3 [1066.1]	23.8 [46.0]
HD 43834 A	5594	0.93	0.92	49.3 [85.2]	4.4 [7.4]	1.14	1.24	55.5 [96.1]	4.6 [7.6]	1.60	2.06	68.3 [141.8]	5.0 [8.9]
HD 46588 A	6204	1.32	1.39	77.4 [160.0]	5.2 [8.9]	1.86	1.86	91.4 [214.2]	5.6 [11.2]	2.20	3.01	131.2 [406.9]	6.7 [17.3]
HD 46582	6066	1.33	1.43	41.7 [89.8]	2.8 [5.4]	1.61	1.92	46.5 [101.9]	2.9 [5.5]	2.23	3.12	56.6 [122.5]	2.9 [5.7]
HD 50281	4767	0.48	0.38	42.2 [79.9]	7.1 [11.2]	0.60	0.52	48.1 [91.9]	7.2 [12.0]	0.86	0.90	59.3 [113.6]	7.2 [13.0]
HD 50692	5924	1.12	1.14	40.1 [73.9]	3.1 [5.7]	1.37	1.54	43.9 [80.8]	3.1 [5.6]	1.90	2.51	52.0 [95.6]	3.1 [5.5]
HD 53705	5790	1.21	1.31	60.4 [108.7]	4.5 [7.7]	1.48	1.76	67.4 [122.7]	4.6 [7.7]	2.06	2.90	84.8 [171.9]	5.1 [8.6]
HD 55575	5902	1.19	1.22	34.7 [65.4]	2.8 [5.1]	1.45	1.64	38.8 [72.9]	2.9 [5.2]	2.02	2.69	46.7 [89.3]	2.9 [5.3]
HD 58655	6349	1.52	1.74	568.9 [1245.8]	38.0 [75.0]	1.84	2.32	716.2 [1749.5]	43.2 [92.3]	2.52	3.72	1101.2 [3015.1]	57.0 [219.2]
HD 65907 A	5997	1.12	1.12	13.9 [31.5]	1.0 [2.1]	1.36	1.50	16.2 [34.9]	1.0 [2.2]	1.88	2.45	20.3 [39.5]	1.1 [2.2]
HD 69830	5423	0.78	0.72	13.2 [28.8]	1.3 [2.6]	0.96	0.98	14.6 [32.6]	1.3 [2.7]	1.36	1.64	17.3 [37.3]	1.3 [2.7]
HD 69897	6269	1.52	1.67	235.5 [450.6]	15.1 [26.2]	1.84	2.23	261.3 [503.4]	15.3 [26.4]	2.53	3.59	323.9 [613.4]	16.1 [27.3]
HD 72673	5261	0.64	0.56	10.6 [20.3]	1.3 [2.4]	0.79	0.76	11.9 [23.0]	1.3 [2.4]	1.12	1.29	14.2 [27.8]	1.4 [2.5]
HD 72905	5893	0.97	0.93	90.2 [167.9]	77.4 [131.1]	1.19	1.24	96.4 [1852.3]	77.4 [131.6]	1.65	2.04	116.2 [2164.4]	76.7 [131.5]
HD 75732 A	5292	0.81	0.74	62.1 [112.7]	6.6 [10.5]	0.99	1.01	70.5 [128.0]	6.9 [10.6]	1.40	1.71	85.5 [159.1]	7.2 [11.6]
HD 76151	5780	0.98	0.96	84.1 [178.2]	7.4 [14.9]	1.19	1.29	98.2 [226.6]	7.8 [16.9]	1.66	2.13	133.2 [363.2]	9.0 [22.2]
HD 78366	5992	1.11	1.12	280.6 [529.2]	21.6 [35.4]	1.35	1.51	318.1 [595.3]	22.1 [36.7]	1.87	2.46	397.8 [754.2]	23.5 [40.9]
HD 84117	6163	1.37	1.51	81.7 [143.7]	5.6 [9.5]	1.67	2.02	89.3 [156.4]	5.7 [9.6]	2.30	3.27	104.6 [186.1]	5.7 [9.8]
HD 84737	5893	1.65	2.04	33.3 [59.2]	2.1 [3.4]	2.01	2.75	37.7 [65.4]	2.1 [3.5]	2.80	4.50	47.0 [84.4]	2.2 [3.9]
HD 86728 A	5743	1.17	1.26	32.0 [62.6]	2.7 [4.7]	1.42	1.70	36.3 [72.9]	2.8 [5.0]	1.99	2.80	45.1 [94.3]	2.9 [5.5]
HD 88230	4097	0.34	0.25	49.1 [90.0]	9.4 [14.7]	0.42	0.34	54.5 [98.1]	9.4 [15.0]	0.62	0.62	65.8 [121.6]	9.5 [16.1]
HD 90839	6164	1.24	1.27	181.0 [348.6]	13.2 [24.0]	1.50	1.70	208.3 [401.9]	13.8 [24.9]	2.07	2.75	277.4 [581.3]	15.8 [29.2]
HD 95128	5880	1.24	1.34	34.9 [269.6]	2.7 [22.4]	1.51	1.80	38.2 [263.9]	2.7 [21.8]	2.10	2.95	45.1 [165.6]	2.8 [9.2]

HD 95735	3601	0.15	0.09	2.3 [4.8]	0.9 [1.6]	0.19	0.12	2.6 [5.6]	0.9 [1.7]	0.28	0.23	3.6 [7.6]	1.0 [1.9]
HD 100623 A	5196	0.62	0.52	20.6 [38.1]	2.5 [4.3]	0.76	0.70	23.3 [42.2]	2.5 [4.2]	1.08	1.20	27.6 [49.6]	2.6 [4.2]
HD 101501	5491	0.78	0.72	62.4 [115.7]	6.6 [10.7]	0.96	0.97	71.2 [133.0]	6.8 [11.0]	1.35	1.62	88.0 [163.1]	7.1 [11.6]
HD 102365	5618	0.92	0.87	17.1 [34.0]	1.6 [2.9]	1.12	1.18	18.8 [37.4]	1.6 [3.0]	1.57	1.95	22.2 [42.7]	1.6 [3.0]
HD 102870	6123	1.85	2.36	115.8 [276.8]	6.2 [14.4]	2.25	3.16	131.1 [337.2]	6.3 [15.6]	3.10	5.12	155.4 [455.7]	6.4 [18.0]
HD 103095	5057	0.47	0.35	137.2 [291.2]	23.4 [44.1]	0.58	0.48	154.1 [347.6]	23.8 [46.7]	0.83	0.82	191.5 [443.6]	24.6 [49.5]
HD 109358	5878	1.06	1.05	47.0 [89.9]	3.9 [6.7]	1.29	1.41	54.1 [102.0]	4.0 [7.1]	1.80	2.32	67.2 [132.8]	4.3 [7.8]
HD 110897	5889	1.03	0.98	33.9 [62.7]	3.1 [5.5]	1.26	1.32	37.0 [71.6]	3.1 [5.6]	1.75	2.17	45.9 [110.6]	3.4 [6.7]
HD 114613	5688	2.05	2.94	42.0 [99.1]	2.3 [4.9]	2.50	3.97	48.7 [144.0]	2.5 [5.9]	3.50	6.57	69.8 [264.2]	3.0 [9.4]
HD 114710	5996	1.15	1.17	386.6 [709.9]	30.6 [52.0]	1.39	1.56	434.8 [779.5]	31.0 [51.6]	1.93	2.55	519.6 [879.4]	31.1 [49.4]
HD 115404 A	4984	0.57	0.49	108.7 [187.4]	15.5 [25.5]	0.70	0.67	118.1 [204.8]	15.4 [25.2]	1.01	1.16	133.5 [229.3]	14.7 [24.4]
HD 115617	5552	0.91	0.88	13.3 [26.7]	1.3 [2.4]	1.19	1.19	14.6 [29.8]	1.3 [2.4]	1.56	1.99	16.9 [34.9]	1.3 [2.3]
HD 122064	4867	0.56	0.48	10.9 [22.1]	1.5 [2.7]	0.68	0.65	12.6 [25.3]	1.6 [2.8]	0.99	1.13	16.3 [31.1]	1.6 [2.9]
HD 128167	6745	1.71	1.89	1003.1 [2042.5]	64.0 [118.2]	2.06	2.51	1117.4 [2295.0]	65.2 [120.8]	2.80	3.97	1336.5 [2769.5]	68.6 [125.7]
HD 128260	5776	1.22	1.29	93.0 [171.2]	7.4 [13.8]	1.49	1.73	116.5 [194.9]	8.1 [13.0]	2.08	2.85	167.1 [436.5]	9.3 [22.6]
HD 128621	5244	0.72	0.63	36.5 [530.9]	3.8 [57.5]	0.88	0.86	42.7 [875.9]	3.9 [87.5]	1.25	1.45	51.4 [1489.8]	4.0 [124.3]
HD 131156 A	5487	0.75	0.66	194.1 [350.9]	20.8 [34.9]	0.91	0.89	218.0 [402.2]	21.4 [36.1]	1.29	1.49	267.9 [514.9]	22.7 [40.0]
HD 131977	4632	0.49	0.40	41.4 [70.9]	7.0 [10.8]	0.60	0.55	46.2 [82.0]	7.0 [11.0]	0.88	0.97	57.2 [103.3]	7.0 [11.5]
HD 134083	6435	1.75	2.00	6044.2 [∞]	357.4 [∞]	2.11	2.66	6626.3 [∞]	359.1 [∞]	2.89	4.26	7532.8 [∞]	360.6 [∞]
HD 136352	5685	1.01	1.01	9.5 [17.1]	0.9 [1.5]	1.23	1.36	10.1 [17.8]	0.8 [1.4]	1.73	2.25	11.3 [20.7]	0.8 [1.4]
HD 140538 A	5682	0.91	0.90	44.8 [86.1]	4.1 [7.7]	1.11	1.21	50.1 [95.1]	4.1 [7.8]	1.56	2.00	61.8 [126.3]	4.4 [8.7]
HD 140901 A	5602	0.90	0.88	123.9 [230.8]	11.8 [19.6]	1.10	1.18	143.7 [259.4]	12.3 [20.2]	1.55	1.97	182.7 [327.7]	13.2 [22.0]
HD 141004	5898	1.40	1.58	38.0 [73.7]	2.8 [5.3]	1.70	2.13	44.0 [84.7]	2.9 [5.4]	2.37	3.49	54.0 [106.0]	3.0 [5.8]
HD 142373	5820	1.76	2.24	244.6 [454.1]	14.2 [25.3]	2.14	3.01	270.1 [518.1]	14.3 [25.8]	2.98	4.95	316.4 [671.2]	14.4 [27.7]
HD 142860	6285	1.70	1.98	769.0 [1451.0]	50.0 [85.5]	2.06	2.64	866.8 [1653.8]	51.1 [89.5]	2.82	4.25	1044.9 [2093.6]	53.0 [100.0]
HD 143761	5812	1.33	1.57	21.1 [49.7]	1.5 [3.3]	1.63	2.11	24.3 [54.2]	1.5 [3.3]	2.27	3.47	29.7 [60.5]	1.6 [3.2]
HD 146233	5785	1.04	1.05	21.0 [39.2]	1.8 [3.2]	1.27	1.41	23.8 [46.1]	1.8 [3.3]	1.77	2.32	30.4 [78.0]	2.0 [4.3]
HD 147513	5868	0.99	0.95	319.3 [699.4]	27.3 [54.2]	1.21	1.28	388.6 [951.4]	29.7 [62.9]	1.68	2.10	575.3 [1730.4]	36.8 [92.2]
HD 149661	5262	0.69	0.61	61.8 [120.7]	7.4 [13.6]	0.85	0.83	70.6 [136.9]	7.6 [13.7]	1.20	1.41	90.2 [169.1]	8.1 [14.3]
HD 156026	4476	0.41	0.32	13.6 [24.3]	2.4 [4.1]	0.51	0.44	15.6 [28.2]	2.5 [4.2]	0.75	0.79	20.0 [36.0]	2.6 [4.3]
HD 162674 A	5235	0.68	0.59	31.9 [55.2]	3.7 [5.9]	0.84	0.81	35.0 [64.7]	3.8 [6.2]	1.19	1.37	42.1 [91.9]	3.9 [7.5]
HD 157214	5704	1.13	1.24	35.9 [66.3]	2.9 [5.1]	1.38	1.67	40.2 [73.4]	3.0 [5.1]	1.93	2.77	48.7 [88.4]	3.1 [5.3]
HD 158633	5302	0.65	0.56	14.1 [26.4]	1.7 [3.1]	0.80	0.76	15.5 [29.5]	1.6 [3.1]	1.13	1.29	17.9 [35.2]	1.6 [3.1]
HD 160691	5761	1.37	1.60	30.4 [227.9]	2.0 [17.6]	1.67	2.16	33.8 [232.6]	2.1 [15.0]	2.33	3.56	41.4 [285.0]	2.2 [13.9]
HD 160499	5951	1.30	1.42	128.2 [1364.0]	9.4 [106.6]	1.58	1.91	147.2 [1892.7]	9.7 [145.4]	2.19	3.12	189.2 [4539.6]	10.4 [273.7]
HD 166620	5028	0.62	0.55	14.5 [28.8]	1.9 [3.4]	0.76	0.75	16.1 [33.1]	1.9 [3.4]	1.09	1.28	19.7 [40.9]	2.0 [3.6]
HD 182572	5593	1.31	1.53	35.5 [65.0]	2.7 [4.5]	1.60	2.07	39.3 [72.2]	2.7 [4.6]	2.24	3.45	48.2 [93.4]	2.9 [5.0]
HD 185144	5298	0.67	0.58	8.5 [17.9]	1.1 [2.2]	0.82	0.79	9.7 [21.0]	1.1 [2.3]	1.16	1.34	12.5 [29.0]	1.2 [2.4]
HD 189567	5730	1.01	1.01	27.7 [54.6]	2.4 [4.5]	1.24	1.36	31.8 [62.6]	2.6 [4.7]	1.73	2.25	39.7 [80.4]	2.7 [5.0]
HD 190248	5576	1.12	1.22	10.0 [23.6]	0.8 [2.0]	1.37	1.65	11.3 [25.5]	0.8 [2.0]	1.92	2.75	13.6 [29.0]	0.9 [1.9]
HD 190360	5563	1.08	1.15	16.5 [61.4]	1.4 [4.6]	1.32	1.55	19.2 [78.1]	1.4 [5.3]	1.86	2.58	22.3 [86.6]	1.4 [5.5]
HD 191408 A	4980	0.55	0.46	20.8 [38.0]	2.8 [4.7]	0.67	0.63	23.0 [44.0]	2.9 [4.9]	0.96	1.08	27.6 [55.4]	2.9 [5.2]
HD 192310	5087	0.65	0.60	7.8 [18.6]	1.0 [2.2]	0.80	0.81	9.0 [21.8]	1.0 [2.3]	1.14	1.39	11.7 [29.0]	1.1 [2.5]
HD 193664	5930	1.04	1.02	49.4 [121.5]	4.5 [8.4]	1.27	1.37	62.7 [166.6]	5.0 [10.3]	1.76	2.24	101.4 [270.3]	6.5 [14.8]
HD 201091	4441	0.39	0.30	13.5 [25.7]	2.7 [4.9]	0.49	0.41	15.3 [28.9]	2.8 [5.1]	0.71	0.73	19.2 [38.3]	3.0 [5.5]
HD 201092	4107	0.29	0.20	6.0 [11.5]	1.7 [3.0]	0.37	0.28	6.7 [13.2]	1.7 [3.1]	0.54	0.50	8.2 [16.4]	1.7 [3.2]
HD 202560	3874	0.31	0.22	39.1 [176.9]	6.6 [12.0]	0.38	0.31	47.5 [89.9]	6.9 [12.5]	0.57	0.56	61.2 [109.7]	7.4 [12.8]
HD 206860	5939	1.05	1.04	552.8 [1026.9]	46.7 [81.2]	1.28	1.39	609.7 [1132.6]	46.6 [81.4]	1.78	2.28	733.2 [1317.5]	46.4 [82.0]
HD 207129	5935	1.08	1.09	40.8 [86.1]	3.5 [6.7]	1.32	1.46	47.7 [105.1]	3.7 [7.6]	1.83	2.38	62.6 [146.6]	4.1 [9.0]
HD 209100	4641	0.49	0.40	14.5 [29.0]	2.9 [4.9]	0.60	0.55	17.1 [33.2]	3.0 [5.2]	0.88	0.97	22.4 [41.4]	3.2 [5.5]
HD 210302	6364	1.66	1.91	141.7 [303.9]	9.1 [18.3]	2.01	2.54	153.0 [321.3]	9.0 [18.0]	2.75	4.08	177.1 [362.6]	9.1 [18.0]
HD 212330 A	5660	1.65	2.09	283.9 [4472.8]	15.5 [245.5]	2.01	2.82	336.5 [6138.4]	16.9 [310.3]	2.82	4.68	500.4 [13243.1]	21.7 [465.1]
HD 213845 A	6605	1.79	2.06	2469.4 [5230.1]	140.5 [269.4]	2.16	2.73	2738.5 [5809.3]	141.6 [273.2]	2.94	4.34	3445.5 [8053.3]	150.7 [317.3]
HD 215648 A	6193	2.08	2.69	359.3 [727.2]	18.2 [32.7]	2.53	3.59	400.2 [795.3]	18.3 [33.1]	3.48	5.81	470.8 [926.8]	18.5 [34.1]
HD 216803	4601	0.46	0.37	219.4 [370.0]	3.1 [4.6]	0.57	0.51	244.1 [404.9]	3.1 [4.6]	0.83	0.89	294.7 [492.2]	3.1 [4.6]
HD 217987	3680	0.20	0.13	9.0 [17.2]	2.2 [4.1]	0.25	0.18	10.2 [19.5]	2.2 [4.2]	0.38	0.34	12.9 [24.3]	2.3 [4.4]
HD 219134	4874	0.53	0.45	9.8 [23.5]	1.4 [3.3]	0.65	0.61	11.0 [26.5]	1.4 [3.4]	0.94	1.05	13.4 [32.5]	1.4 [3.6]
HD 219623	6084	1.40	1.53	104.3 [199.9]	8.2 [14.8]	1.70	2.05	113.6 [217.7]	8.0 [14.5]	2.35	3.32	133.0 [256.7]	7.8 [14.8]
HD 222368	6200	1.79	2.18	192.4 [343.1]	11.0 [18.9]	2.17	2.92	210.7 [377.7]	10.8 [19.0]	2.99	4.71	250.8 [483.6]	11.2 [20.1]

Note. Values in brackets ("[]") denote the sensitivity limit defined by the 90% completeness contour (opposed to the CL₅₀ 50% completeness contour).

† Computed in installation flux space.

(A machine-readable version of the full table in Harada et al. (2025) is available at the publisher's website.)

Table 4.A7: RV Sensitivity Limits for the Conservative HZ.

HD Name	R.A. ($^{\circ}$)	Decl. ($^{\circ}$)	T_{eff} (K)	$\log L_*/L_{\odot}$	$\log R'_{\text{HK}}$
HD 739	2.933421	-35.13311	6495.0	0.4814	-4.715
HD 4813	12.53162	-10.64433	6208.0	0.2506	-4.865
HD 7788 A	18.94204	-68.87594	6436.0	0.5911	-4.272
HD 17206	41.27583	-18.57262	6330.0	0.4178	-4.461
HD 23754	56.71203	-23.24972	6685.0	0.7049	-4.855
HD 33262 A	76.37773	-57.4727	6158.0	0.1662	-4.426
HD 33564	80.63971	+79.23115	6354.0	0.5171	-4.979
HD 35296	81.1061	+17.38354	6131.0	0.2499	-4.378
HD 64379	118.0653	-34.70544	6525.0	0.4043	-4.363
HD 74576	130.8251	-38.88238	4992.0	-0.4982	-4.351
HD 82885 A	143.9146	+35.81013	5518.0	-0.1057	-4.638
HD 90589	156.0988	-74.03161	6905.0	0.7128	-4.685
HD 90089 A	157.7696	+82.55865	6758.0	0.5124	-4.55
HD 105452 A	182.1034	-24.72888	6990.0	0.6487	-4.214
HD 114837 A	198.5631	-59.10324	6238.0	0.4722	-4.665
HD 126660 A	216.2992	+51.85074	6280.0	0.6054	-4.361
HD 155886	258.8366	-26.6017	5132.0	-0.4848	-4.57
HD 155885	258.8374	-26.60283	5144.0	-0.4788	-4.559
HD 156897 A	260.2516	-21.11294	6756.0	0.6161	
HD 160032	265.0993	-49.41558	6620.0	0.6579	-4.665
HD 160915	265.8575	-21.68319	6404.0	0.4315	-4.698
HD 165341 B	271.3644	+2.498947	4475.0	-0.7843	-4.71
HD 165185	271.5988	-36.01979	5892.0	0.0186	-4.406

Table 4.A8: Stars with No Public RV Data.

4.B Systems with Updated Planet Parameters

As discussed in the main text of this chapter, at least 70 exoplanets (of which at least 9 have been disputed) have previously been detected around 30 of the 164 stars in the sample (Section 4.6). Of the known planets, we detected a total of 51 orbiting 21 different stars. The updated masses and orbital properties of these planets are shown in Table 4.A4. We also detected signals associated with two known stellar companions. While some of these systems were discussed in the main text in Section 4.5, here, we briefly discuss our results for the rest of these systems individually.

HD 3651 A (54 Psc A)

HD 3651 A (54 Psc A; HIP 3093 A; HR 166 A; GJ 27 A; TIC 434210589) is a K0.5V star (Keenan and McNeil 1989) at a distance of $d = 11.108 \pm 0.006$ pc (Gaia Collaboration 2022a). This star hosts an eccentric planet (54 Psc b; $e \approx 0.645$) with an orbital period of $P \approx 62.25$ days and a minimum mass of $M_p \sin i \approx 72.5 M_{\oplus}$ (Wittenmyer et al. 2019). The planet 54 Psc b has been studied extensively in the literature using observations from various instruments, including Hamilton/Shane at Lick Observatory (Fischer et al. 2003), HIRES/Keck (Butler et al. 2006), and the

High Resolution Spectrograph (HRS)/Hobby-Eberly Telescope (HET) at McDonald Observatory (Wittenmyer et al. 2009). Here, we robustly detected 54 Psc b at $P \approx 62.25$ days with 461 RVs from the HIRES, HRS, Hamilton, Levy, and Tull instruments spanning 30 yr. We found a Keplerian orbital solution for this planet consistent with previous studies (see Table 4.A4). We also report an additional Keplerian signal with a period of $P = 5157$ days, which has previously been attributed to long-period magnetic SA (R21). We also note the presence of a signal in the S -index GLS periodogram at $P \approx 3500$ days, which may also be due to a magnetic activity cycle (e.g., Isaacson et al. 2024).

HD 9826 A (ν And A)

HD 9826 A (Titawin; ν And A; HIP 7513 A; HR 458 A; GJ 61 A; TIC 189576919) is an F8V star in a binary system (Gray et al. 2001) at a distance of $d = 13.49 \pm 0.03$ pc (van Leeuwen 2007). At least three giant planets are known to orbit ν And A, which were initially detected with RV observations obtained at the Lick and Whipple Observatories (Butler et al. 1997, 1999). The orbits and masses of the three planets, ν And b, c, and d, were subsequently refined with additional RVs from ELODIE/OHP (Naef et al. 2004). Tull/Harlan J. Smith (HJS) spectrograph (Wittenmyer et al. 2007), and HRS/HET (McArthur et al. 2010), in addition to astrometry from the Hubble Space Telescope (HST; McArthur et al. 2010). Evidence for a fourth planet was later reported by Curiel et al. (2011), who detected a 3848.9 day signal (corresponding to a $M_p \sin i = 1.06 M_J$ planet) using a novel detection algorithm and archival RV data. We report six Keplerian signals using a total of 853 RVs collected using the AFOE, ELODIE, Hamilton, HIRES, HRS, Levy, SOPHIE, and Tull instruments across 30 yr. Three of the signals found by RVSearch match the known planets. Two additional signals with orbital periods of 3150 and 174.35 days found by RVSearch were previously attributed to SA and instrumental systematics, respectively, by R21. Lastly, we note that RVSearch identified a long-period signal with an orbital period of 32,946 days, although this signal does not have sufficient orbital phase coverage to be properly classified.

HD 10647 (q^1 Eri)

HD 10647 (q^1 Eri; HIP 7978; HR 506; GJ 3109; TIC 229137615) is an F9V star (Keenan and McNeil 1989) at a distance of $d = 17.35 \pm 0.01$ pc (Gaia Collaboration 2022a) with one known planet (q^1 Eri b) and an asymmetric debris disk (Stencel and Backman 1991; Liseau et al. 2008; Lovell et al. 2021). The planet q^1 Eri b is an eccentric ($e \approx 0.15$) giant ($M_p \sin i = 299 M_\oplus$) on a $P \approx 989.2$ day orbit (Marmier et al. 2013). It was initially detected using 28 RVs from UCLES/AAT, and was later reobserved using CORALIE (Marmier et al. 2013). We recovered the planet again here using 226 RVs from the HARPS, UCLES, Coudé Échelle Spectrometer + Long Camera (CES-LC), Coudé Échelle Spectrometer + Very Long Camera (CES-VLC), and CORALIE instruments across 26 yr. The derived planet parameters are consistent with those previously reported in Marmier et al. (2013).

HD 17051 (*t* Hor)

HD 17051 (*t* Hor; HIP 12653; HR 810; GJ 108; TIC 166853853) is an F9V Fe+0.3 star (Gray et al. 2006) at a distance $d = 17.36 \pm 0.01$ pc (Gaia Collaboration 2022a). The star has one known giant ($M_p \sin i \approx 677 M_\oplus$) planet (HR 810 b) with an orbital period of $P \approx 312$ days (Butler et al. 2001). The planet HR 810 b was discovered with RV observations from the ESO Coudé Auxiliary Telescope Spectrograph at La Silla (Kürster et al. 2000) and UCLES/AAT at the Australian National University (Butler et al. 2001). We recovered the planet here at a period of $P \approx 308$ days using 228 HARPS, CES-LC, CES-VLC, CORALIE, and UCLES RVs with an orbital solution consistent with previous studies. We also identified a signal with $P = 383.0 \pm 2.2$ days. We classified this signal as a likely systematic FA, as its orbital period is close to a sidereal year, and there are corresponding subthreshold peaks in the H -index, R'_{HK} , BIS, and FWHM periodograms and a significant peak in the window function periodogram.

HD 20794 (82 Eri)

HD 20794 (82 Eri; HIP 15510; HR 1008; GJ 139; TIC 301051051) is a G6V star (Keenan and McNeil 1989) with evidence of a circumstellar debris disk (Wyatt et al. 2012; Montesinos et al. 2016) at a distance of $d = 6.041 \pm 0.003$ pc (Gaia Collaboration 2022a). The star hosts a multi-planet system of at least two low-planets, HD 20794 b and HD 20794 d, with orbital periods of $P_b \approx 18.3$ days and $P_d \approx 90.3$ days and masses of $M_{p,b} \sin i \approx 2.7 M_\oplus$ and $M_{p,d} \sin i \approx 4.8 M_\oplus$ (Pepe et al. 2011). Here, we detected both known planets using 858 RVs collected by ESPRESSO, HARPS, PFS, and UCLES. Interestingly, we note the presence of a weakly significant peak in the H -index periodogram consistent with the orbital period of planet d at ~ 90 days, suggesting that perhaps a more detailed look into the SA patterns of the host star near this period is warranted. We also detected a significant RV signal at 364.2 days that is not associated with any known planets or PCs; we classified this signal as an FA due to its consistency with the sidereal year. We also found significant peaks at this period in the R'_{HK} , BIS, FWHM, and window function periodograms.

We also note that this system has been suggested to host two additional low-mass planets, HD 20794 c ($P_c \approx 40.1$ days; Pepe et al. 2011) and HD 20794 e ($P_e \approx 147.0$ days; (Feng et al. 2017a)), which were not detected in this analysis. Although the planetary signals originally reported at 18 and 90 days (corresponding to planets b and d) were “very significant,” Feng et al. (2017a) cautioned that their detection of a possible planet c at 40 days was “less apparent” in the phase-folded RV plot and that the “orbital period is close to the supposed rotational period of the parent star,” casting some doubt as to whether the signal was real or not. An independent reanalysis of the HARPS data using a more sophisticated treatment of correlated noise later found only “weak evidence” for the 40 day signal (Feng et al. 2017a), and a more recent analysis of data from HARPS/ESO, UCLES/AAT, and PFS/Magellan also failed to detect the reported signal at 40 days (L23). Our analysis of the combined ESPRESSO, HARPS, PFS, and UCLES data further suggests that the 40 day signal is not real. A recent analysis by Nari et al. (2025) confirmed that the 40 day signal is due to stellar rotation. Additionally, Feng et al. (2017a) reported two more potential new detections at 147 and 330 days. Neither of these signals were detected by L23, and we did not

find evidence of them in this study either. Cretignier et al. (2023) also claimed a 10σ detection of a $< 1 \text{ m s}^{-1}$ signal at 650 days using the HARPS data. This was subsequently confirmed by Nari et al. (2025), who notably did not find evidence of the 147 day signal (making this a disputed planet). Although we did not detect the 147 and 650 day signals, given the more sophisticated data reduction and analysis of stellar variability and correlated noise by the Feng et al. (2017a) and Nari et al. (2025) studies, we cannot rule them out as potential candidate planets. Lastly, we note that an apparent instrumental drift in the ESPRESSO RVs may have limited the sensitivity of our analysis of this system, as correcting instrumental red noise is beyond the scope of this work.

HD 22049 (ϵ Eri)

HD 22049 (Ran, ϵ Eri; HIP 16537; HR 1084; GJ 144; TIC 118572803) is a K2V star (Keenan and McNeil 1989) at a distance of $d = 3.220 \pm 0.001 \text{ pc}$ (Gaia Collaboration 2022a). The star’s young age (200–800 Myr; Fuhrmann 2004; Mamajek and Hillenbrand 2008) and prominent debris disk (e.g., Greaves et al. 1998; Backman et al. 2009) make ϵ Eri a particularly interesting system. This star hosts at least one known planet (ϵ Eri b) on a $P = 2671 \text{ day}$ (7.3 yr) orbit with a minimum mass of $M_p \sin i = 209.8 M_\oplus$ (Llop-Sayson et al. 2021). The planet was first announced by Hatzes et al. (2000), who analyzed six independent RV data sets taken at four ground-based telescopes. Subsequently, it has been extensively observed and characterized in various studies spanning the last least three decades, both from the ground (e.g., Mawet et al. 2019) and from space (e.g., Benedict et al. 2006; Llop-Sayson et al. 2021). With our data set of 693 total RVs from HIRES, HARPS, CES-LV, CES-VLC, EXPRES, Hamilton, Levy, and Tull, we detected ϵ Eri b at a period of $2686.0 \pm 18.0 \text{ days}$, consistent with previous values. A significant S -index signal in the activity GLS periodogram at $P \approx 1100 \text{ days}$ is consistent with the known magnetic activity cycle of this star (Metcalf et al. 2013).

HD 39091 (π Men)

HD 39091 (π Men; HIP 26394; HR 2022; GJ 9189; TIC 261136679) is a G0V star (Gray et al. 2006) with evidence of a debris disk (Sibthorpe et al. 2018) at a distance of $d = 18.29 \pm 0.01 \text{ pc}$ (Gaia Collaboration 2022a). The star hosts a multiplanet system consisting of at least three planets. The planet π Men b was initially published by Jones et al. (2002) based on observations from the UCLES spectrograph. The second planet, π Men c, was the first planet discovered by TESS and is consistent with a super-Earth on a 6.3 day orbit (Gandolfi et al. 2018; Huang et al. 2018). The third planet, π Men d, was identified with EPRV observations from ESPRESSO (Hatzes et al. 2022) with a period of $P_d = 125 \text{ days}$, and later confirmed by L23. In this work, we detected the giant planet π Men b at $P = 2088.82 \pm 0.31 \text{ days}$ using 415 HARPS, ESPRESSO, CORALIE, PFS, and UCLES RVs. Our orbital solution is consistent with recent estimates by Feng et al. (2022), Hatzes et al. (2022), and L23. We also detected planet c with a precise period of $P = 6.26815 \pm 0.00045 \text{ days}$ and planet d at an orbital period of $120.3 \pm 0.1 \text{ days}$.

HD 69830

HD 69830 (HIP 40693; HR 3259; GJ 302; TIC 307624961) is a G8+V star (Gray et al. 2006) with a debris disk (Beichman et al. 2005; Trilling et al. 2008) at a distance of $d = 12.579 \pm 0.006$ pc (Gaia Collaboration 2022a). The star hosts three known planets, which were initially detected after 2 yr of HARPS RV observations (Lovis et al. 2006). The planets all have minimum masses consistent with sub-Neptunes and orbital periods between 8 and 200 days. In this work, we recovered the planets HD 69830 b, HD 69830 c, and HD 69830 d with periods $P_b = 8.6690 \pm 0.0005$ days, $P_c = 31.613 \pm 0.009$ days, and $P_d = 201.1 \pm 0.5$ days. The periods and masses are consistent with recently published values (R21; L23). We also detected a signal at $P = 379$ days consistent with a signal identified by R21, which we classified as FA due to the strong peak in the window function at this period.

HD 75732 A (55 Cnc A)

HD 75732 A (Copernicus; 55 Cnc A; HIP 43587 A; HR 3522 A; GJ 324 A; TIC 332064670) is a well-known K0IV-V star (Gray et al. 2003) at a distance of $d = 12.587 \pm 0.007$ pc (Gaia Collaboration 2022a). This star hosts five planets, which have been abundantly observed and characterized over many years (see, e.g., Fischer et al. 2008; Endl et al. 2012; Bourrier et al. 2018, and references therein). In this work, we analyzed 876 RVs spanning 31 yr from the ELODIE, HARPS-North, HIRES, HRS, Hamilton, Levy, SOPHIE, and Tull spectrographs, and recovered 55 Cnc b, c, d, e, and f with masses and orbits consistent with previous studies. We also detected a signal at $P = 10585 \pm 2400$ days, which is consistent with the second harmonic of the known SA cycle period around 13 yr (e.g., Baluev 2015).

HD 95128 (47 UMa)

HD 95128 (Chalawan; 47 UMa; HIP 53721; HR 4277; GJ 407; TIC 21535479) is a G1-V Fe-0.5 star (Keenan and McNeil 1989) at a distance of $d = 13.89 \pm 0.02$ pc (Gaia Collaboration 2022a). This star hosts a well-studied planetary system with three long-period planets. The first planet, 47 UMa b, was published by Butler and Marcy (1996) based on data from the Hamilton spectrograph at Lick Observatory. It was later suggested that the system hosted a second planet (Fischer et al. 2002; Naef et al. 2004; Wittenmyer et al. 2007, 2009) and, later, a third planet (Gregory and Fischer 2010; R21) based on additional RV measurements and more sophisticated analysis techniques. Using 585 RVs from the HIRES, ELODIE, HRS, Hamilton, Levy, and Tull instruments, we detected 47 UMa b and 47 UMa c at periods of $P_b = 1076.1 \pm 1.2$ days and $P_c = 2265 \pm 15$ days, which are consistent with previous measurements. We did not directly detect 47 UMa d, which has an orbital period of $\sim 14,000$ days (about 38 yr). Planet d was detected by Gregory and Fischer (2010), who developed a hybrid MCMC model that could constrain the long orbital period of the planet despite sampling data from only a fraction of the orbital period (Table 4.A6). In this work, we detected a long-period signal at about 17,650 days, which is likely associated with 41 UMa d. However, because our regular MCMC analysis was unable to converge

on a single value, we did not classify this as a detection of planet d. Lastly, we also detected an FA signal at 358.3 days, which was close to the sidereal year and had corresponding peaks in the H -index and window function GLS periodograms.

HD 95735 (Lalande 21185)

HD 95735 (Lalande 21185; HIP 54035; GJ 411; TIC 166646191) is an M2V star (Kirkpatrick et al. 1991) at a distance of $d = 2.5461 \pm 0.0002$ pc (Gaia Collaboration 2022a). A PC with $M_p \sin i = 2.99 M_\oplus$ was initially detected orbiting this star on a 12.95 day orbit using 157 RVs from SOPHIE/OHP (Díaz et al. 2019). The planet (GJ 411 b) was later confirmed by archival HIRES data and new RVs from the CARMENES spectrograph at Calar Alto Observatory (Stock et al. 2020). With additional RV observations from APF, a second planet in the system (GJ 411 c) with $M_p \sin i = 13.6 M_\oplus$ was later confirmed at a period of about 2900 days (Hurt et al. 2022). The authors also reported a possible third planet with a period near 215 days and $M_p \sin i = 3.89 M_\oplus$. In this work, we analyzed 762 RVs collected using the CARMENES, HIRES, Hamilton, and Levy instruments. We recovered GJ 411 b and GJ 411 c at $P_b = 12.938 \pm 0.002$ days and $P_c = 2801 \pm 81$ days and masses consistent with those reported in the literature. However, we note that the sparse RV phase coverage of planet c and presence of significant power at long periods in the GLS periodograms of FWHM, BIS, and $EW_{H\alpha}$ bring into question the planetary nature of this signal. We recommend further analysis to rule out SA as the culprit. We also identified a signal at 55.32 days, corresponding to the measured stellar rotation of HD 95735 reported in Hurt et al. (2022).

HD 115617 (61 Vir)

HD 115617 (61 Vir; HIP 64924; HR 5019; GJ 506; TIC 422478973) is a G6.5V star (Keenan and McNeil 1989) with a circumstellar debris disk (Trilling et al. 2008; Tanner et al. 2009; Wyatt et al. 2012) at a distance of $d = 8.53 \pm 0.01$ pc (Gaia Collaboration 2022a). This star hosts a multiplanet system discovered with observations from HIRES and UCLES, which consists of three planets with orbital periods of approximately 4.2, 38, and 124 days (Vogt et al. 2010). In this work, with 773 RVs from the HARPS, HIRES, PFS, UCLES, Hamilton, and Levy instruments, we recovered all three planets at orbital periods of $P_b = 4.21501 \pm 0.00009$ days, $P_c = 38.086 \pm 0.005$ days, and $P_d = 123.15 \pm 0.16$ days. These parameters are consistent with recent estimates from L23. We also detected a long-period RV signal at 4026.3 days, which is similar to the LPS identified for this system by L23. While this signal may correspond to a magnetic activity cycle, additional data are required to confirm its true nature.

HD 136352 (v^2 Lupi)

HD 136352 (v^2 Lupi; HIP 75181; HR 5699; GJ 582; TIC 136916387) is a G2-V star (Gray et al. 2006) at a distance of $d = 14.74 \pm 0.01$ pc (Gaia Collaboration 2022a). Three planets were detected in this system based on HARPS RV observations (Udry et al. 2019), and were later detected in

transit with observations from TESS (Kane et al. 2020) and CHEOPS (Delrez et al. 2021). In this work, we used 463 RVs spanning 22 yr from the HARPS, HIRES, PFS, and UCLES instruments. We recovered all three known planets with parameters consistent with recently published values (e.g., L23).

HD 141004 (λ Ser)

HD 141004 (λ Ser; HIP 77257; HR 5868; GJ 598; TIC 296740796) is a G0-V star (Keenan and McNeil 1989) at a distance of $d = 11.92 \pm 0.02$ pc (Gaia Collaboration 2022a). R21 reported a detection of a sub-Neptune planet ($M_p \sin i = 13.6 \pm 1.5 M_\oplus$) with an orbital period of 15.5 days. In this work, we analyzed 553 RVs spanning 32 yr collected using the HIRES, Hamilton, and Levy spectrographs. We detected the planet at $P_b = 15.509 \pm 0.002$ days with properties consistent with those reported in R21.

HD 143761 (ρ CrB)

HD 143761 (ρ CrB; HIP 78459; HR 5968; GJ 9537; TIC 458494003) is a G0+Va Fe-1 star (Keenan and McNeil 1989) at a distance of $d = 17.51 \pm 0.02$ pc (Gaia Collaboration 2022a). A giant planet was initially detected at a period of about 39 days from RV data obtained with the AFOE instrument at Whipple Observatory (Noyes et al. 1997). A second lower-mass planet was later reported based on additional RV measurements from HIRES and APF (Fulton et al. 2016). Recently, Brewer et al. (2023) obtained EPRV observations of this system using EXPRES/Lowell Discovery Telescope. In addition to refining the masses and orbits of ρ CrB b and c, Brewer et al. (2023) reported two new planets in the system with orbital periods of $P_d \approx 282.2$ days ($M_{p,d} \sin i \approx 21.6 M_\oplus$) and $P_e \approx 12.949$ days ($M_{p,e} \sin i \approx 3.79 M_\oplus$). Our analysis of 552 RVs spanning 26 yr recovered the planets discovered by Noyes et al. (1997) and Fulton et al. (2016) with periods of $P_b = 39.8434 \pm 0.0004$ days and $P_c = 102.58 \pm 0.04$ days. We also detected a signal at 267.8 ± 1.7 days with $M_p \sin i = 13.5 \pm 2.3 M_\oplus$, corresponding to ρ CrB d identified in Brewer et al. (2023). The final residual periodogram of the RVs shows a fourth signal at 12.9 days, which corresponds to planet e (Brewer et al. 2023). However, likely due to the small amplitude of this planet’s RV signal ($\approx 1 \text{ m s}^{-1}$), the FAP of the 12.9 day signal was 0.27%—too high to be considered a bona fide detection in this work (Table 4.A6).

HD 160691 (μ Ara)

HD 160691 (Cervantes; μ Ara; HIP 86796; HR 6585; GJ 691; TIC 362661163) is a G3IV-V star (Gray et al. 2006) at a distance of $d = 15.60 \pm 0.02$ pc (Gaia Collaboration 2022a). HD 160691 is a closely studied multiplanet system, which was first discovered by the Anglo-Australian Planet Search using the UCLES spectrograph (Butler et al. 2001; Jones et al. 2002). Subsequent ground-based observing campaigns with instruments including HARPS and CORALIE confirmed four planets in the system (McCarthy et al. 2004; Santos et al. 2004; Goździewski et al. 2007; Pepe et al. 2007), and more recently, HST Fine Guidance Sensor astrometry was used to further refine the

masses and orbits of the planets (Benedict et al. 2022). In this work, we analyzed 351 RVs collected over 21 yr using the HARPS, PFS, and UCLES instruments. We detected all four of the known planets at periods of $P_b = 644.93 \pm 0.27$ days, $P_c = 4241 \pm 145$ days, $P_d = 9.6392 \pm 0.0008$ days, and $P_e = 308.54 \pm 0.22$ days, consistent with previously published results (Pepe et al. 2007).

HD 165499 (*t* Pav)

HD 165499 (*t* Pav; HIP 89042; HR 6761; GJ 9616; TIC 303704858) is a G0V star (Gray et al. 2006) at a distance of $d = 17.75 \pm 0.04$ pc (Gaia Collaboration et al. 2018). HD 165499 is a binary star system, initially identified by Barbato et al. (2023). Using a combination of CORALIE RVs and proper-motion anomalies between HIPPARCOS (Perryman et al. 1997) and Gaia epochs, they found that the binary has an orbital period of $P \approx 6.2$ yr (8.6 ± 0.3 au) and mass of $M \sin i = 141 \pm 10 M_J$. In this work, we used 65 CORALIE RVs spanning 22.5 yr and clearly detected the binary companion. We reported a period of $P = 8296 \pm 25$ days ($a = 8.6 \pm 0.5$ au) and minimum mass of $139.8 \pm 14.6 M_J$, consistent with Barbato et al. (2023). We did not detect any significant SA signals or additional planetary signals. However, this system is noteworthy due to its binarity; multiple star systems may pose substantial challenges for starlight suppression for coronagraphic observations. The EMSL excluded unresolved spectroscopic binaries and binaries with angular separations $< 3''$ (Mamajek and Stapelfeldt 2024) based on properties published in the Washington Visual Double Star Catalog (WDS; Mason et al. 2001) and the Ninth Catalog of Spectroscopic Binary Orbits (Pourbaix et al. 2004). The small physical separation of this binary and the distance to the system imply a maximum angular separation $< 1''$. Therefore, it should have been excluded from the EMSL. We note that this system may not be a suitable target for HWO unless future coronagraphic instruments can effectively mask starlight from a close-by off-axis companion.

HD 189567

HD 189567 (HIP 98959; HR 7644; GJ 776; TIC 352402781) is a G2V star (Gray et al. 2006) at a distance of $d = 17.932 \pm 0.008$ pc (Gaia Collaboration 2022a). This star hosts two known planets at periods of approximately 14.3 and 33.7 days with minimum masses of $8.8 M_\oplus$ and $7.2 M_\oplus$ (Mayor et al. 2011; Unger et al. 2021). Here, we detected both planets and measured their orbits and masses to values consistent with previous estimates based on 260 RVs from HARPS. We also found evidence for a long-term quadratic trend in the RVs (Table 4.A5).

HD 212330 A

HD 212330 A (HIP 110649 A; HR 8531 A; GJ 857 A; TIC 259291108) is a G2IV-V star (Gray et al. 2006) at a distance of $d = 20.34 \pm 0.04$ pc (Gaia Collaboration 2022a). This star is in a binary system with an orbital period of $\sim 16,000$ days (~ 44 yr) and a true companion mass of $663 \pm 77 M_J$ ($\approx 0.63 M_\odot$; Kane and Blunt 2019; Barbato et al. 2023). In this work, we used 79 CORALIE RVs and detected the binary companion with orbital parameters consistent with those reported in Barbato et al. (2023). The orbital parameters and distance to this system imply

a maximum angular separation less than $1''$. As was the case for HD 165499, this small angular separation is not consistent with the EMSL binary criteria set by Mamajek and Stapelfeldt (2024), so the star should have been excluded from the list. Interestingly, this star is flagged as a binary on the EMSL (WDS designation 22249–5748), but the WDS angular separation and Δmag are given as $23''.6$ and 7.68 mag, respectively, which *are* allowed by the EMSL criteria. It is possible that this star is a hierarchical multistar system with a wide-separation component at $23''.6$ and a much closer inner component. This may be consistent with the long-term quadratic trend observed in the CORALIE RVs, in addition to the $\sim 16,000$ day orbit of the inner stellar companion. Nonetheless, we note that this system may not be a suitable target for HWO depending on how well future coronagraphs are able to suppress off-axis stellar companions.

4.C Nondetections in Systems with Previously Reported Planets

Our RV analysis did not recover 19 of the 70 previously reported planets in the sample. At least nine of these nondetections were of planets that have been disputed by subsequent papers or were not detailed in the original discovery paper. In some cases, auxiliary observations from either imaging or astrometry were used in the original study, which are beyond the scope of this paper. In other cases, the discovery data may not have been published, or the statistical significance of a potential RV signal was not adequate to be classified as a detection in this work. A summary of the undetected planets is given in Table 4.A6. In the following subsections, we briefly discuss the systems where we did not detect any planetary signals that were previously identified in the literature. Other nondetections in systems where at least one additional planet was successfully detected are discussed in Section 4.5 or Appendix 4.B.

HD 10700 (τ Cet)

HD 10700 (τ Cet; HIP 8102; HR 509; GJ 71; TIC 419015728) is a G8V star (Keenan and McNeil 1989) with a debris disk (e.g., Greaves et al. 2004; MacGregor et al. 2016; Sibthorpe et al. 2018) at a distance of $d = 3.652 \pm 0.002$ pc (Gaia Collaboration 2022a). Notably, τ Cet has the single highest number of RV observations in our sample ($N_{\text{RV}} = 1692$), yielding the highest sensitivity to HZ planets of the Sun-like stars in the sample. Previously, Tuomi et al. (2013) identified up to five possible planets in this system, of which two (e and f) were also later detected by Feng et al. (2017b). The authors of the latter study used a “differential radial velocity” model that accounted for wavelength-dependent noise in the RV data to identify four PCs with $M_p \sin i < 4 M_\oplus$ (RV amplitudes down to 0.3 m s^{-1}) and orbital periods between 20 and 637 days (see Table 4.A6). However, the existence of any planets in this system has been called into question in recent work. For example, Korolik et al. (2023) used long-baseline interferometric data and high-precision spectroscopic observation to measure τ Ceti’s stellar inclination, and found a near-polar orbit. This architecture would mean that the planets reported in Feng et al. (2017b) may not remain dynamically stable, calling into question whether there are currently planets orbiting this star. We detected a

single Keplerian signal with our analysis, which we classified as an FA due to its small amplitude and proximity to the $1/3$ annual harmonic. We did not identify any subthreshold peaks in the RV residuals that correspond to any of the putative planets reported in Feng et al. (2017b). We attribute our nondetection to the more sophisticated treatment of wavelength-dependent noise in previous studies and the disputed nature of these planets.

HD 33564

HD 33564 (HIP 25110; HR 1686; GJ 196; TIC 142103211) is an F7V star (Gray et al. 2003) at a distance of $d = 20.79 \pm 0.03$ pc (Gaia Collaboration 2022a). A single massive ($M_p \sin i = 9.1 M_J$) planet, HD 33564 b, has been reported in this system with an orbital period of 388 days (Galland et al. 2005) using only 15 RV measurements from the ELODIE spectrograph spanning one orbital period. The ELODIE data analyzed by Galland et al. (2005) are not publicly available apart from the data points plotted in Figure 1 of that study. To the best of our knowledge, HD 33564 has not been observed by any of the instruments included in this analysis. The limited RV data analyzed in the discovery paper and lack of follow-up observations make HD 33564 b a dubious planet detection.

HD 86728 A

HD 86728 A (20 LMi A; HIP 49081; HR 3951; GJ 376; TIC 172954294) is a G3V star at a distance of $d = 14.92 \pm 0.02$ pc (Bailer-Jones et al. 2021). A single planet on a circular orbit at $P = 31.1503 \pm 0.0066$ days was detected using NEID in Gupta et al. (2025) and found to have a minimum mass of $M_p \sin i = 9.16 \pm 0.56 M_\oplus$. We identified a subthreshold peak at 31.2 days in 445 RVs from the HIRES, Hamilton, Levy, and NEID instruments. However, this peak did not pass the $FAP = 0.01$ threshold, and is only statistically significant in the NEID RVs.

HD 102365

HD 102365 (HIP 57443; HR 4523; GJ 442 A; TIC 454082369) is a G2V star (Gray et al. 2006) at a distance of $d = 9.319 \pm 0.008$ pc (Gaia Collaboration 2022a). The star has one known planet, HD 102365 b, which was discovered using 12 yr of UCLES data (Tinney et al. 2011). The mass ($M_p \sin i = 16.0 \pm 2.6 M_\oplus$) and orbit ($P = 122.1 \pm 0.3$ days) of this planet were later confirmed and refined using additional RVs from HIRES, HARPS, and PFS (L23). Strangely, we did not detect HD 102365 b in this work despite analyzing 373 RVs from HARPS, HIRES, CES-LC, CES-VLC, PFS, and UCLES. In the instrument-by-instrument GLS periodogram of the RVs, a significant ~ 120 signal is clearly present. However, this peak only appears in the UCLES RV periodogram. This suggests that the 122 day signal may be an instrumental effect associated with UCLES. It may also be that the lower-precision measurements from CES-LC and CES-VLC effectively dilute the UCLES signal to the point where it disappears from the periodogram. We recommend an additional follow-up analysis of this signal to determine whether it is a bona fide planet or instrumental systematic.

HD 115404 A

HD 115404 A (HIP 64797 A; GJ 505 A; TIC 373765355) is a K2.5V (k) star (Gray et al. 2003) at a distance of $d = 10.987 \pm 0.003$ pc (Gaia Collaboration 2022a). This star was recently suggested to host two PCs from a combined analysis of HIRES RVs and Hipparcos–Gaia astrometry (Feng et al. 2022). However, the original study reporting these planets does not detail the analysis of the RVs and astrometry for this system specifically. We were unable to detect either planet with only 95 RVs from ELODIE, HIRES, and SOPHIE. While the astrometry data may be necessary to recover these putative planets, we treat them as disputed planets in this work because the discovery paper does not discuss this system specifically, and there have been no subsequent follow-up studies of the system to confirm the planets.

HD 140901 A

HD 140901 A (HIP 77358 A; HR 5864 A; GJ 599 A; TIC 179348425) is a G7IV-V star (Gray et al. 2006) at a distance of $d = 15.246 \pm 0.008$ pc (Gaia Collaboration 2022a). Using both RV observations and astrometric data from Gaia and Hipparcos, Feng et al. (2022) reported two PCs with orbital periods of about 9.0 and 7417.5 days (≈ 20.3 yr). The long-period planet was later confirmed by (Philipot et al. 2023), although the presence of the inner planet at 9 days remains controversial (and is flagged as such on the NASA Exoplanet Archive). We did not recover either of these signals in our analysis of 172 HARPS, PFS, and UCLES RVs spanning 21.9 yr. We attribute these nondetections to the controversial nature of the inner planet, and the use of astrometric data in (Philipot et al. 2023) to identify the longer-period planet.

HD 147513

HD 147513 (HIP 80337; HR 6094; GJ 9559; TIC 350673608) is a G1V CH-0.4 star (Gray et al. 2006) at a distance of $d = 12.89 \pm 0.01$ pc (Gaia Collaboration 2022a). This star hosts one known giant planet, which was initially detected using 30 RV measurements from CORALIE spanning about 4.6 yr, but has not since been confirmed by follow-up observations. It was reported to have an orbital period of $P \approx 528$ days and a minimum mass of $M_p \sin i \approx 1.21 M_J$ (Mayor et al. 2004). Interestingly, adding 46 nights of more recent HARPS RVs to the analysis in this study causes the planet’s signal to vanish. With the combined RVs, we only detected a subthreshold peak in the RV periodogram at 504.1 days, which did not meet the $FAP = 0.01$ requirement. We suggest further analysis of the CORALIE and HARPS RVs of this system to determine whether the HD 147513 b is a real planet.

HD 206860 (HN Peg)

HD 206860 (HN Peg; HIP 107350; HR 8314; GJ 9751; TIC 301880196) is a G0IV-V star (Gray et al. 2003) with a debris disk (Trilling et al. 2008; Ertel et al. 2012) at a distance of $d = 18.13 \pm 0.01$ pc (Gaia Collaboration 2022a). HN Peg has a T dwarf companion, HD 206860 b, at a physical

separation of 795 ± 15 au, which was discovered via direct imaging with the Spitzer Space Telescope (Luhman et al. 2007). In this work, we analyzed 89 RVs from the Hamilton and Levy instruments spanning about 31 yr. However, given the extremely long orbital period of HD 206860 b, the RV baseline was simply much too short to probe this directly imaged planet’s long-period parameter space.

HD 209100 (ϵ Ind)

HD 209100 (ϵ Ind; HIP 108870; HR 8387; GJ 845 A; TIC 231698181) is a K4V(k) star (Gray et al. 2006) at a distance of $d = 3.638 \pm 0.001$ pc (Gaia Collaboration 2022a). A combined analysis of Gaia–Hipparcos astrometry and archival RVs led to the discovery of a Jupiter-analog planet (ϵ Ind b) in this system with a mass of $\sim 3 M_J$ on a slightly eccentric orbit with a period of about 45 yr (Feng et al. 2019). This planet was recently imaged with the James Webb Space Telescope using the MIRI coronagraphic imager (Matthews et al. 2024), which suggested that the planet has a high-metallicity, high carbon-to-oxygen atmosphere. We were unable to detect ϵ Ind b here using only the 266 RV measurements from HARPS, CES-LC, CES-VLC, and Ultraviolet and Visual Échelle Spectrograph (UVES) that span 29 yr. This was due to the lack of additional information provided by imaging or astrometric observations in our analysis. However, we were able to detect a long-term quadratic trend in the RVs that is likely caused by the planet.

4.D Classifications of Other Signals Detected

Here, we comment on systems with other RV signals detected by RVSearch, which have not yet been discussed in Section 4.5 or Appendices 4.B–4.C. These systems have no previously detected planets, so the signals discussed here are either related to SA or instrumental FAs.

HD 1581 (ζ Tuc)

HD 1581 (ζ Tuc; HIP 1599; HR 77; GJ 17; TIC 425935521) is an F9.5V star (Gray et al. 2006) at a distance of $d = 8.61 \pm 0.01$ pc (Gaia Collaboration 2022a). This star has no known exoplanets, although an observed infrared excess suggests the presence of a circumstellar debris disk (Trilling et al. 2008). We analyzed 550 RV observations of this target from HARPS, CES-LC, CES-VLC, and UCLES spanning a total of 29 yr. We found two significant signals at $P_{01} = 937.0 \pm 16.5$ days (~ 2.6 yr) and $P_{02} = 15.654 \pm 0.006$ days. This target was predicted to have a stellar rotation rate of $P_{\text{rot}} = 16.7 \pm 2.6$ days (Lovis et al. 2011), which matches the 15.65 day RV signal we detected. We have therefore designated signal HD 1581.01 as SA-R (indicating rotation-modulated SA). Lovis et al. (2011) also reported an SA cycle for HD 1581 with a period of $P_{\text{cycle}} = 1018^{+51}_{-47}$ days, based on 127 R'_{HK} measurements from HARPS. This activity period is consistent with our second RV detection (HD 1581.01) within 2σ ; therefore, we categorized this signal as being due to SA. This interpretation is supported by a peak in the FWHM GLS periodogram at ~ 1000 days.

HD 4614 A (η Cas A)

HD 4614 A (Achird; η Cas A; HIP 3821 A; HR 219 A; GJ 34 A; TIC 445258206) is a F9V star (Keenan and McNeil 1989) at a distance of $d = 5.010 \pm 0.003$ pc (Gaia Collaboration 2022a). This target has no known planets, and we identified one RV signal at 91.02 days using 273 observations from HIRES, SOPHIE, Hamilton, and Levy spanning 24 yr. This signal was previously classified as an annual and/or instrumental systematic by R21. We classified this signal as an FA due to the period being similar to the 1/4 annual harmonic and dubious RV phase curve.

HD 14412

HD 14412 (HIP 10798; HR 683; GJ 95; TIC 72748794) is a G8V star (Gray et al. 2006) at a distance of $d = 12.835 \pm 0.005$ pc (Gaia Collaboration 2022a). There are no previously known planets orbiting this star. In this work, we used 400 RVs collected by HARPS, HIRES, UCLES, PFS, and Levy across 23.1 yr. We identified one RV signal at 361.7 days, which we classified as an FA due to its proximity to 1 yr, as demonstrated by the strong peak near 1 yr in the window function GLS periodogram for this target.

HD 20807 (ζ 2 Ret)

HD 20807 (ζ 2 Ret; HIP 15371; HR 1010; GJ 138; TIC 279649049) is a G1V star in a binary star system (Keenan and McNeil 1989) at a distance of $d = 12.039 \pm 0.009$ pc (Gaia Collaboration 2022a). There are no previously known planets in this system. In this work, we analyzed 323 RVs from CES-LC, CES-VLC, HARPS, UCLES, and PFS and identified one RV signal at $P = 2943 \pm 130$ days. We observe moderate correlations between the RVs and the SA data, and a peak in the R'_{HK} periodogram consistent with the signal. This suggests that the RV signal is due to underlying SA. Using HARPS spectra, Lovis et al. (2011) characterized the magnetic cycle of HD 20807 and found a period of $P = 1133 \pm 700$ days. Additional work by Flores et al. (2021) identified a $P = 2899 \pm 139$ day (≈ 7.9 yr) chromospheric activity cycle for this star using 430 spectra. We therefore classified the 2943 day signal found in our analysis as being due to SA.

HD 23249 (δ Eri)

HD 23249 (Rana; δ Eri; HIP 17378; HR 1136; GJ 150; TIC 38511251) is a K0+IV star (Keenan and McNeil 1989) at a distance of $d = 9.09 \pm 0.02$ pc (Gaia Collaboration 2022a). This target has no previously known planets. In this work, we used 512 RVs collected across 27 yr using the CES-LC, CES-VLC, HARPS, HIRES, SOPHIE, UCLES, and Levy instruments. Using RVSearch, we identified one RV signal at $P = 595.3 \pm 4.2$ days. Recently, L23 found a nearly identical signal using a subset of the data analyzed here, which they categorized as an SRC. We do not find evidence of significant SA correlations or signals in the GLS periodograms, so we do not associate the signal with SA. Due to the highly eccentric dubious phase curve of the RVs and the lack of a well-defined

peak in the RV periodogram, we deemed this signal unlikely to be physical and classified it as an FA.

HD 26965 A (40 Eri A)

HD 26965 A (Keid, 40 Eri A; HIP 19849 A; HR 1325 A; GJ 166 A; TIC 67772871) is a K0.5V standard star (Gray et al. 2006) at a distance of $d = 5.010 \pm 0.003$ pc (Gaia Collaboration 2022a). An RV signal near 43 days was first detected using data from HARPS, HIRES, PFS, and the CTIO High Resolution Spectrometer (CHIRON), which the authors were unable to classify as either planetary or SA due to the similarity between the star’s rotation period and the period of the RV signal (Díaz et al. 2018). A subsequent analysis by Ma et al. (2018) later suggested that the 43 day signal was indeed due to a planet after analyzing additional RV data. However, subsequent deep dives into the nature of this signal have revealed that it is indeed most likely due to SA and not a planet. Recently, it was shown that a combination of spots and convective blueshift suppression likely created this signal (Burrows et al. 2024; Siegel et al. 2024). Here, we detected the RV signal at $P = 42.322 \pm 0.015$ days using 666 RVs from the HARPS, HIRES, PFS, UCLES, Hamilton, and Levy spectrographs. Following the previous studies, we classified this signal as SA-R in Table 4.A4. We also identified a signal with a period of $P = 37.326 \pm 0.021$ days, which has been attributed to differential stellar rotation. We classified this signal as SA-R. Lastly, we note the detection of a known magnetic activity cycle at $P \approx 3000$ days in the residual RV periodogram (as a nonsignificant peak), as well as the S -index and R'_{HK} GLS periodograms (Lovis et al. 2011; Garg et al. 2019; Isaacson et al. 2024).

HD 32147

HD 32147 (HIP 23311; HR 1614; GJ 183; TIC 213041474) is a K3+V star (Gray et al. 2003) at a distance of $d = 8.844 \pm 0.002$ pc (Gaia Collaboration 2022a) with no known planets. Our analysis of 352 RVs from HIRES, HARPS, PFS, Hamilton, and Levy spanning 33.3 yr revealed a single Keplerian signal at $P_{01} = 3127 \pm 120$ days (~ 8.6 yr), which also appears as a prominent peak in the RV GLS periodogram. Previously, Garg et al. (2019) measured two activity cycles for this star with periods of $P_{\text{cyc}} = 9.33$ yr ($= 3407.8$ days) and $P_{\text{cyc}} = 12.42$ yr ($= 4536.4$ days). The former activity cycle period is consistent with our RV detection (HD 32147.01) to within 2σ , so we classified it as SA. This activity signal was also detected by R21 at $P = 3444.0^{+91.0}_{-81.0}$ days and by Isaacson et al. (2024) at a period of 9.53 yr ($= 3480.8$ days).

HD 38858

HD 38858 (HIP 27435; HR 2007; GJ 1085; TIC 176521059) is a G2V star (Gray et al. 2003) at a distance of $d = 15.210 \pm 0.007$ pc (Gaia Collaboration 2022a). There are no known planets orbiting this star. Previous work identified a stellar magnetic activity cycle with a period of $P = 3460^{+2151}_{-570}$ days (Lovis et al. 2011), which was also reported in L23 at $P = 2893 \pm 150$ days and in R21 at $P = 3113.0 \pm 80$ days. In this work, we used 223 RVs from HARPS, HIRES, and Levy

and identified one RV signal at $P = 417.4 \pm 3.8$ days. This corresponds to the yearly alias of the previously measured stellar magnetic activity cycle, and we therefore classified this signal as SA.

HD 46588 A

HD 46588 A (HIP 32439 A; HR 2401 A; GJ 9215 A; TIC 141523112) is an F8V star (Gray et al. 2003) at a distance of $d = 18.2 \pm 0.02$ pc (Gaia Collaboration 2022a). This star has a common proper-motion companion at the L/T spectral type transition with a projected physical separation of 1420 au (Loutrel et al. 2011). In this work, we used 347 RVs from CARMENES and the Stellar Observations Network Group échelle spectrometer (SONG) spanning 4.1 yr, and identified four RV signals using RVSearch. These signals have orbital periods of 121.81 ± 0.54 days (HD 46588.01), 181 ± 1 days (HD 46588.02), 410 ± 4 days (HD 46588.03), and 899^{+2000}_{-240} days (HD 46588.04). Previous work searching for planets orbiting stars with wide brown dwarf companions identified three Keplerian signals in the RV data of HD 46588 A with periods of 127, 224, and 365 days (Šubjak et al. 2023). Due to the strong correlation between the chromatic index and CARMENES RVs, Šubjak et al. (2023) classified the 127 day peak as SA due to the star’s magnetic cycle, which was strengthened by the SONG H α data. They also attributed the 1 yr peak to the SONG window function. Following Šubjak et al. (2023), we classified HD 46588.01 as SA, but we did not see clear evidence of the 224 day peak reported in that study. Rather, the other three signals we detected are likely FAs due to corresponding periodicity in the observational window function. The window function periodogram for this star is quite complex with multiple peaks. The signals we detected at 181, 410, and 889 days all correspond to significant peaks in the window function periodogram or the annual alias of a significant peak.

HD 48682 (56 Aur)

HD 48682 (56 Aur; HIP 32480; HR 2483; GJ 245; TIC 307754027) is an F9V star (Gray et al. 2003) at a distance of $d = 16.61 \pm 0.02$ pc (Gaia Collaboration 2022a). There are no known planets in this system, and it may host an extended, cold debris disk (Hengst et al. 2020). In this work, we analyzed 361 RVs collected using HIRES, Hamilton, and Levy spanning 32.5 yr. We identified one significant signal in the RVs at 929.2 ± 4.9 days, which was previously identified as SA by R21. We note that RV phase plot for this signal is not well described by the model, and the peak in the periodogram is not well defined. Following R21, we classified this signal as SA.

HD 76151

HD 76151 (HIP 43726; HR 3538; GJ 327; TIC 62569281) is a G2V star (Keenan and McNeil 1989) at a distance of $d = 16.85 \pm 0.01$ pc (Gaia Collaboration 2022a). There are no known planets in this system, but it may have a circumstellar disk as indicated by infrared excess (Eiroa et al. 2013). In this work, we used 150 HARPS, HIRES, Hamilton, and Levy RVs spanning 32.3 yr to identify one Keplerian RV signal at 1850 ± 24 days. This system was recently analyzed by L23, but the authors did not report any significant RV signals. However, Baliunas et al. (1995) identified

an SA cycle period of 2.52 ± 0.02 yr (~ 920 days). The signal we identified at 1850 days is very close to the second harmonic of this known activity period. Additionally, the periodogram peak we observe is not well defined, and we measure significant correlations between the H -index and BIS activity indicators and the RVs. We therefore classified this signal as SA.

HD 102870 (β Vir)

HD 102870 (Zavijava; β Vir; HIP 57757; HR 4540; GJ 449; TIC 366661076) is an F9V star (Morgan and Keenan 1973) at a distance of $d = 10.93 \pm 0.03$ pc (van Leeuwen 2007). There are no known planets orbiting this target. In this work, we used 346 RVs collected using the HARPS, SOPHIE, Levy, Hamilton, and Tull instruments, and identified one Keplerian signal at 2167 ± 43 days. We note that Seach et al. (2022) used Zeeman Doppler Imaging to measure the surface magnetic field of this star, and measured a rotation period of ≈ 9.1 days, which is inconsistent with the longer-period signal we found with RVSearch. We found a significant correlation between the Tull RVs and S -Index measurements ($r = 0.29$, $p = 0.0014$), which may suggest that the signal is related to SA. However, there are no significant peaks in the activity GLS periodograms, except for a strong peak in the window function at ≈ 2000 days. We interpret this window function periodicity as evidence that the 2167 day RV signal is due to an observational bias. Therefore, we classified this signal as an FA.

HD 114613

HD 114613 (HIP 64408; HR 4979; GJ 9432; TIC 30293512) is a G4IV star (Gray et al. 2006) at a distance of $d = 20.46 \pm 0.04$ pc (Gaia Collaboration 2022a). The star was observed as part of the Anglo-Australian Planet Search, and was initially found to host a PC on a ~ 10.5 yr orbit based on RV measurements from UCLES (Wittenmyer et al. 2014). Although the amplitude and period of the putative planet were refined by Luhn et al. (2019), additional measurements from Keck later showed an activity correlation, which subsequently led Luhn et al. (2020) to attribute the signal to activity-induced RV jitter (the current disposition of HD 114613 b on the NASA Exoplanet Archive at the time of writing is “false-positive planet”).

In our analysis of 534 HIRES, HARPS, CES-LC, CES-VLC, UCLES, and PFS RVs, we detected an RV signal at $P = 3851 \pm 34$ days, which is consistent with the signal (now known to be caused by SA) first reported by Wittenmyer et al. (2014). We note that the recent study by L23 did not report this signal in their analysis of RVs from HARPS, HIRES, and PFS, but instead found signals at approximately 6622, 73, and 1954 days (reported as SA or SRCs). We did not detect any of these signals in this work, but did detect an additional signal at 4814 ± 260 days. Because of significant correlations between the RVs and activity data, and significant power at long periods ($\gtrsim 2000$ days) in the periodograms for H -index, R'_{HK} , BIS, and FWHM, we determined the nature of this signal also to be SA. The multitude of signals in previous studies of the RVs and activity indicator data for this system are likely the result of increased stellar jitter due to the evolved nature of HD 114613 (Luhn et al. 2020).

HD 128620/128621 (α Cen A/B)

HD 128620 (Rigil Kentaurus; α Cen A; HIP 71683; HR 5459; GJ 559 A; TIC 471011145) and HD 128621 (Toliman; α Cen B; HIP 71681; HR 5460; GJ 559 B; TIC 471011144) are a well-known binary system consisting of a G2V star (α Cen A; Gray et al. 2006) and a K1V star (α Cen B; Torres et al. 2006) at a distance of $d = 1.3319 \pm 0.0007$ pc (Akeson et al. 2021). As one of the closest and brightest multistar systems, this system has been studied extensively in the literature (e.g., Zhao et al. 2018, and references therein). There are no confirmed planets orbiting either star, although recent JWST/MIRI imaging observations have suggested there may be a giant planet in the HZ of α Cen A (Beichman et al. 2025; Sanghi et al. 2025), and past RV work has suggested an Earth-mass planet orbiting α Cen B (Dumusque et al. 2012). The α Cen B planet has since been ruled out as a planet and attributed to a window function systematic and SA (Hatzes 2013).

Here, we analyzed 278 RVs of α Cen A collected with CES-LC, CHIRON, and CTIO Échelle Spectrometer (CTIO-ES) and 632 RVs of α Cen B collected with CES-LC, CHIRON, CTIO-ES, and HARPS. We observed significant long-term trends in the RVs consistent with the stars' orbits around their common barycenter. We also identified two Keplerian signals in the α Cen B data at $P = 333.9 \pm 1.3$ days and $P = 62.34 \pm 0.3$ days. Both signals are dubious given the multiple clustered peaks in both Δ BIC periodograms and the nonmonotonically increasing running-Lomb–Scargle periodograms. The first signal is also consistent with an annual systematic, seen as a series of peaks in the window function GLS periodogram. We classified both signals as FAs. We note that the putative giant planet in α Cen A (Beichman et al. 2025; Sanghi et al. 2025) has a suggested mass below the RV sensitivity limit, which explains why we did not detect a signal associated with this PC. For α Cen B, we identified one significant long-period signal (LPS) at $P \approx 12,600$ days after modeling out the long-term RV trend associated with the stellar binary. This signal is consistent with significant power in the BIS, FWHM, and window function GLS periodograms, but given that the limited RV data cannot sample the full orbit, this signal is likely a systematic.

HD 140538 A (ψ Ser A)

HD 140538 A (ψ Ser A; HIP 77052 A; HR 5853 A; GJ 9527 A; TIC 459427073) is a solar-twin G5V star (Gray et al. 2001) with no known planets at a distance of $d = 14.793 \pm 0.008$ pc (Gaia Collaboration 2022a). We analyzed 160 RVs from HIRES, HARPS, and Levy spanning a total of 17.6 yr. We found one significant RV signal at $P = 1449 \pm 17$ days (~ 4.0 yr), which matches a very strong peak in the S -index GLS periodogram. This is a well-studied signal that has been attributed to a stellar magnetic activity cycle by multiple past studies (e.g., Mittag et al. 2019b; R21; Isaacson et al. 2024). We therefore classified the signal as SA.

HD 146233 (18 Sco)

HD 146233 (18 Sco; HIP 79672; HR 6060; GJ 616; TIC 135656809) is a solar-twin G2Va standard star (Keenan and McNeil 1989) at $d = 14.14 \pm 0.01$ pc (Gaia Collaboration 2022a) with no known

exoplanets. Our analysis included 440 RV data points taken over a 23.5 yr span from HIRES, HARPS, Levy, PFS, and UCLES. We detected one RV signal at $P = 2435 \pm 31$ days (~ 6.7 yr), which is also present in the R'_{HK} , BIS, and window function periodograms below the significance threshold. This signal has been identified previously as SA, with literature values ranging from 6.27 yr (~ 2290 days; Isaacson et al. 2024) to 2803^{+2663}_{-392} days (~ 7.7 yr; Lovis et al. 2011). The activity period we measured is most consistent with the value reported by R21 at $P = 2426^{+60}_{-42}$ days. Following these previous studies, we classified the signal as SA.

HD 158633

HD 158633 (HIP 85235; HR 6518; GJ 675; TIC 219880402) is a K0V star (Cowley et al. 1967) at a distance of $d = 12.792 \pm 0.004$ pc (Gaia Collaboration 2022a). This star hosts no known planets. We used 361 HIRES, SOPHIE, Hamilton, and Levy RVs to identify one significant RV signal at 366.5 ± 1.6 days. This is consistent with the sidereal year and a significant peak in the window function periodogram. As in previous studies of this system (e.g., R21), we classified this signal as an FA.

HD 185144 (σ Dra)

HD 185144 (Alsaifi; σ Dra; HIP 96100; HR 7462; GJ 764; TIC 259237827) is a K0V star (Keenan and McNeil 1989) with no known planets at a distance of $d = 5.764 \pm 0.002$ pc (Gaia Collaboration 2022a). Our analysis of this star included 728 RVs from HIRES, Hamilton, and Levy observed over a span of 24 yr. We identified three significant RV signals at $P_{.01} = 2338 \pm 34$ days (~ 6.4 yr), $P_{.02} = 363.34 \pm 0.69$ days, and $P_{.03} = 121.55 \pm 0.22$ days. The first signal appears as a very strong peak in the S -index GLS periodogram, and we observed a strong correlation between the HIRES S -index data and the RVs. Following past studies of this signal that are consistent with our results (R21; Isaacson et al. 2024), we classified it as a stellar magnetic activity cycle. The second signal sits very close to the annual harmonic and is consistent with the peak in the window function periodogram. We therefore classified it as an FA (R21 detected a similar signal with $P = 347.11^{+0.92}_{-0.82}$, which they labeled “annual and/or instrumental systematic”). The period of the final signal is almost exactly at the $1/3$ annual harmonic and also has a corresponding significant peak in the window function periodogram. We classified this as an FA.

HD 201091/201092 (61 Cyg A/B)

HD 201091 (61 Cyg A; HIP 104214; HR 8085; GJ 820 A; TIC 165602000) and HD 201092 (61 Cyg B; HIP 104217; HR 8086; GJ 820 B; TIC 165602023) are a well-known binary system consisting of a K5V star (61 Cyg A; Keenan and McNeil 1989) and a K7V star (61 Cyg B; Keenan and McNeil 1989) at distances of $d_A = 3.4966 \pm 0.0007$ pc and $d_B = 3.4964 \pm 0.0004$ pc (Gaia Collaboration 2022a). Neither star hosts any known planets. In the RVs we compiled, we see opposite long-term trends for these stars associated with their mutual orbital motions. For 61 Cyg A, we used 300 RVs collected using HIRES, Hamilton, and Levy to identify one significant RV signal

at 6918 ± 40 days, which we classified as a systematic FA due to a corresponding strong peak in the window function at this period. We note that past analysis of this star also detected an SA cycle with a period of ~ 2600 days (R21; Isaacson et al. 2024), which we see weak evidence for in the GLS periodograms for *S*-index and *H*-index. For 61 Cyg B, we analyzed 296 RVs collected using HIRES, Hamilton, and Levy and identified one significant RV signal at 49.012 ± 0.029 days. Past work has attributed this signal to stellar rotation (R21).

HD 207129

HD 207129 (HIP 107649; HR 8323; GJ 838; TIC 147407292) is a G0V Fe+0.4 star (Gray et al. 2006) with an imaged debris disk (Krist et al. 2010; Löhne et al. 2012) at a distance of $d = 15.56 \pm 0.01$ pc (Gaia Collaboration 2022a). The star hosts no known planets. We analyzed 179 RVs from HARPS, CES-LC, and CES-VLC spanning almost 27 yr. We found one RV signal at $P = 1393 \pm 11$ days (~ 3.8 yr), which is consistent to within 1σ of the literature value for this star's activity cycle period ($P = 1520^{+171}_{-139}$ days; Lovis et al. 2011). Additionally, L23 analyzed this system using RV data from HARPS and UCLES, and found an RV signal at $P = 1964 \pm 49$ days and an *S*-index signal at $P \approx 1898$ days, which they attributed to a magnetic activity cycle.

Chapter 5

An Eccentric Giant Companion in the HD 5015 System

In this chapter, I present a preview of ongoing work building upon the results presented in Chapters 3 and 4. I present early results from a new radial velocity (RV) survey at Lick Observatory’s Automated Planet Finder (APF) that actively monitoring stars with sparse previous RV measurements (discussed in Chapter 4). Preliminary measurements reveal an interesting large-amplitude ($\approx 70 \text{ m s}^{-1}$) RV signal in the HD 5015 system. HD 5015 is a late F dwarf in the solar neighborhood ($d = 18.9 \text{ pc}$) that is slightly hotter and more massive than the Sun ($T_{\text{eff}} = 6050 \text{ K}$; $M_{\star} = 1.15 M_{\odot}$). I report updated stellar properties of HD 5015 based on the broadband spectral energy distribution and high-resolution spectra from APF and HIRES, in addition to a stellar rotation period from TESS photometry. I present a preliminary analysis of the large-amplitude RV signal in the APF data using a combination of Lomb–Scargle and χ^2 periodograms and nested sampling. I also report evidence of a stellar magnetic cycle of at least 500 days based on S -index measurements from APF. While the initial results are intriguing, I emphasize that additional work is needed to increase our confidence in the orbital solution from the APF, ELODIE, and HIRES data. Future RV observations will also be instrumental in determining the orbital period and nature of the perturber orbiting HD 5015.

5.1 Introduction

The orbital configuration and properties of the planets in our Solar System represent just one possible outcome of planet formation and evolution. Yet our Solar System is the only one we know to harbor life. Is the particular architecture of our Solar System a requirement for habitable planets to exist, or could there be a diversity of planetary system architectures that are also suitable for life to evolve on temperate rocky worlds? As discussed in Section 1.3 in the Background chapter, the Kepler Mission (Borucki et al. 2010) revealed an astounding diversity in planetary system architectures around FGK stars (e.g., Lissauer et al. 2011; Hsu et al. 2019; Kunimoto and Matthews 2020) and showed that multi-planet systems are common (Sandford et al. 2019; He et al.

2019). Kepler statistics suggest that at as many as 50% of FGK stars host at least one planet between 0.5 and $10 R_{\oplus}$ at orbital periods < 300 days (He et al. 2019).

As we have already discussed earlier in this dissertation (Section 1.3, Chapter 3, and Chapter 4), our knowledge about the prevalence of Earth-like exoplanets and their potential to be habitable will benefit immensely from future space-based high-contrast imaging missions that will directly probe the habitable zones (HZs) of nearby stars (e.g., the Habitable Worlds Observatory). The preliminary work presented in here is the fourth in the series of papers (Harada et al. 2024; Kane et al. 2024; Harada et al. 2025, two of which from earlier chapters), investigating the properties of nearby star systems that are promising targets for future exoEarth surveys.

Thanks to their brightness, many suitable target stars for future exoEarth missions have been observed as part of previous ground-based RV surveys. These past planet searches have revealed at least 70 planetary companions orbiting 30 of the ExEP HWO stars spanning a wide range of system architectures and stellar spectral types. Nearly 85% of these planets reside in multi-planet systems, and $> 90\%$ orbit GKM stars cooler than 6000 K. However, some stars that could be observed by future exoEarth missions have not been previously monitored by RV searches (see Chapter 4 for a discussion).

One example of a star with very few previous RV observations is HD 5015, a bright ($V \approx 4.8$) F8–9V (Hoffleit and Jaschek 1991; Abt 2009) field star located in the constellation Cassiopeia at a distance of $d = 18.896 \pm 0.034$ pc (Bailer-Jones et al. 2021). HD 5015 is slightly hotter and more massive than the Sun ($T_{\text{eff}} = 6045 \pm 100$ K; $M_{\star} = 1.15^{+0.24}_{-0.20} M_{\odot}$; see Section 5.3), with a slightly super-solar metallicity ($[\text{Fe}/\text{H}] = 0.11 \pm 0.06$) and low chromospheric activity ($\log \langle R'_{\text{HK}} \rangle = -5.16 \pm 0.01$). This star hosts no previous reported planets or stellar companions.

In this chapter, we present 71 nights of new RV observations from Lick Observatory’s Automated Planet Finder (APF). Together with 13 nights of archival RVs from OHP/ELODIE and 3 nights of RVs from Keck/HIRES (see Chapter 4), these new data reveal a potential massive object on a high-eccentricity orbit around HD 5015. This potential detection was made possible thanks to the high precision and short cadence of the new APF data compared to the archival data, which were far sparser and easily could have missed the large RV variation we seen in the APF data. I emphasize that the work presented in this chapter is ongoing, and that additional work remains to better characterize the orbit and nature of the object inducing this RV signal.

In Section 5.2, I present the current observations of HD 5015, including the new APF data, archival RVs, and TESS photometry. In Section 5.3, I further discuss the characteristics of the host star. Then, I present a preliminary analysis of the RVs in Section 5.4, followed by a discussion of future directions for this study in Section 5.5.

5.2 Observations

HD 5015 was previously identified as a promising HWO target star by in the ExEP Mission Star List (Mamajek and Stapelfeldt 2024) and characterized by Harada et al. (2024). Then, in a survey of all publicly available RV measurements of the ExEP targets, Harada et al. (2025) found that HD 5015 lacked more than 20 high-precision RV observations from the past 30 years. Here, we

summarize some of the existing observations of HD 5015, and introduce our new observations of the system with APF.

High-resolution Spectroscopy

APF/Levy

The Automated Planet Finder (APF; Vogt et al. 2014; Radovan et al. 2014) is a fully robotic 2.4 m telescope at Lick Observatory feeding into the high-dispersion Levy spectrograph ($R \sim 100,000$), which operates between 374–970 nm. HD 5015 was observed by APF/Levy as part of HWO precursor Doppler survey beginning with programs 2024A_A001 (PI: Holden) and 2025A_A009 (PI: Harada) for a total of 71 nights (312 total exposures) between 2024 May and 2026 March. The median exposure time of these observations was 182 s, resulting in a median RV uncertainty of 0.89 m s^{-1} . Our science observations were made with a warm iodine cell in the optical path for wavelength calibration and reduced following the procedures outlined in Howard et al. (2010). The APF RVs were flat throughout 2024, but they fortuitously began to decline in February 2025 before the trend reversed around August of that year and then leveled off again around February 2026. This resulted in a large rms of 41.5 m s^{-1} . Our APF/Levy observations of HD 5015 remain ongoing (2025B_A002, 2026A_A010; PI: Harada), as more data are needed to determine the orbital period and therefore the minimum mass of the object inducing the trend. The APF observations of HD 5015 we have obtained thus far are plotted in Figure 5.5. The full APF time series data set will be made available in a future publication.

Archival RVs

HD 5015 was previously observed by the CORAVEL instrument (Baranne et al. 1979) on the 1 m Swiss telescope and the ELODIE spectrograph (Baranne et al. 1996) on the 1.93 m telescope at the Observatoire de Haute-Provence (OHP). CORAVEL was an early spectrometer operating between 370–520 nm that was primarily used to characterize stellar kinematics, rotation, and metallicity. While HD 5015 was observed 21 times by CORAVEL between 1979 September and 1989 August (Duquennoy et al. 1991), the large RV uncertainties ($0.2\text{--}0.3 \text{ km s}^{-1}$) and sparse sampling make these data less useful for constraining sub-stellar-mass companions (although they do constrain more massive stellar companions). We therefore do not include the archival CORAVEL data in our analyses.

HD 5015 was later observed 13 times by ELODIE, the upgraded replacement to CORAVEL, between 1997 November and 2002 September (Moultaka et al. 2004). ELODIE was a fiber-fed échelle spectrograph ($R \sim 40,000$) operating at wavelengths of 390–681 nm, allowing it to reach much better RV precision ($7\text{--}10 \text{ m s}^{-1}$). We downloaded the publicly-available ELODIE data from the Data & Analysis Center for Exoplanets (DACE) archive website,¹ which were calibrated using a Th–Ar lamp and reduced using the proprietary ELODIE Data Reduction Software (TACOS).

¹<https://dace.unige.ch/dashboard/>

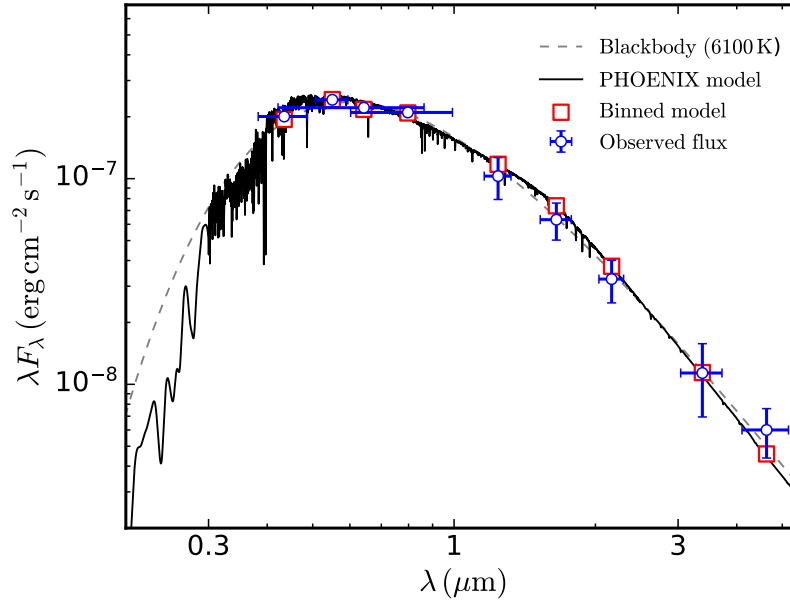


Figure 5.1: Broadband photometry of HD 5015 with best-fit SED model used to derive stellar parameters. The observed photometry (Table 5.1) are shown by the blue circles and the closest-match PHOENIX model is shown in black. Model photometry binned to the same wavelengths as the observations are shown as red squares. The horizontal error bars represent the approximate bandpass width of each filter.

Though sparse, these early data do not show any significant variation and have an rms of about 8 m s^{-1} . The ELODIE data are plotted along with the APF RVs in Figure 5.5.

HD 5015 was also later observed with the High Resolution Échelle Spectrometer (HIRES) on the Keck I telescope on Maunakea (Vogt et al. 1994). A total of 13 Keck/HIRES spectra of HD 5015 were obtained over 3 separate nights between 2008 December and 2009 December, with a typically nightly RV uncertainty of 0.9 m s^{-1} . These observations were made public by the Lick–Carnegie Exoplanet Survey Team (LCES) as part of a larger data release of archival Keck/HIRES (Butler et al. 2017). The LCES data were obtained with a spectral resolving power of $R \sim 60,000$ and a wavelength range of 370–800 nm using an iodine gaseous cell as a precision velocity reference. While the HIRES observations are very sparse, they may still be useful for ruling out certain orbital periods for the long-period object producing the trend seen in the APF data. The HIRES data are also shown in Figure 5.5.

TESS Photometry

HD 5015 (TIC 285544488) was observed by the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2014) over 6 sectors between 2019 October and 2024 November (sectors 17, 18, 24, 58, 78, and 85). We downloaded all two-minute cadence TESS observations of HD 5015 from

the Mikulski Archive for Space Telescopes (MAST)² using the `Lightkurve` package (Lightkurve Collaboration et al. 2018). Throughout this work, we use the Pre-search Data Conditioning Simple Aperture Photometry (PDCSAP), which was extracted using the TESS Science Processing Operations Center (SPOC) data reduction pipeline (Jenkins et al. 2016).

5.3 Stellar Properties

Spectroscopically Derived Parameters

We determined stellar parameters for HD 5015 from the iodine-out APF/Levy spectrum using the `SpecMatch-Synthetic` code³ (Petigura et al. 2017). In brief, `SpecMatch-Synthetic` forward-models 5 segments of the observed optical spectrum by interpolating between a grid of model stellar spectra from Coelho et al. (2005) at discrete values of T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$. The code accounts for line broadening due to convective macroturbulence and stellar rotation (parameterized as $v \sin i$), as well as instrumental profiles. Each spectrum segment is fit individually and then the resulting parameters are averaged. For HD 5015 we find $T_{\text{eff}} = 6045 \pm 100$ K, $\log g = 4.1 \pm 0.1$, $[\text{Fe}/\text{H}] = 0.11 \pm 0.06$, and $v \sin i = 5.2 \pm 1.0$ km s⁻¹. We find a similar set of stellar parameters when analyzing the publicly-available Keck/HIRES spectra using the `SpecMatch-Emp` code⁴ (Yee et al. 2017). `SpecMatch-Emp` takes advantage of a library of over 400 empirical stellar spectra obtained by HIRES with well-determined stellar parameters. The algorithm shifts the observed HIRES spectrum onto the library wavelength scale, identifies the most similar library spectra, then interpolates between them to get the final set of stellar parameters. The stellar parameters (shown in Table 5.1) are consistent between both spectroscopic analyses and the values reported in v8.2 of the TESS Input Catalog (TIC; Stassun et al. 2019; Paegert et al. 2022). Table 5.1 also contains stellar parameters from previous literature sources, which are generally consistent to 1σ given their uncertainties.

Photometrically Derived Parameters

As a cross-check to the spectroscopic analysis, we analyzed the broadband spectral energy distribution (SED) of HD 5015 together with the Gaia DR3 parallax (Gaia Collaboration et al. 2023) to determine the empirical measurement of the stellar mass and radius using the `ARIADNE` package⁵ (Vines and Jenkins 2022). `ARIADNE` is a Bayesian analysis tool for SED modeling that uses nested sampling (Skilling 2004, 2006) and Bayesian model averaging (BMA; Fragoso et al. 2018) to derive robust stellar parameters accounting for systematic biases between different stellar atmosphere models. In brief, `ARIADNE` fits the observed SED by interpolating between multiple stellar model libraries independently (see Vines and Jenkins 2022 or Chapter 3 for a full discussion). The

²<https://archive.stsci.edu>

³<https://github.com/petigura/specmatch-syn>

⁴<https://github.com/samuelyeewl/specmatch-emp>

⁵<https://github.com/jvines/astroariadne>

Parameter	Unit	Value	Source	Adopted?
Other Names		TIC 285544488	TIC v8.2 ^a	
		HIP 4151	Hipparcos–Tycho Catalog ^b	
		HR 244	Bright Star Catalog v5 ^c	
		Gaia 427322415301550208	Gaia DR3 ^d	
Spectral Type		F8V	Bright Star Catalog v5 ^c	
Spectral Type		F9V	Abt (2009)	
R.A. (J2016)	°	13.26685659532	Gaia DR3 ^d	
decl. (J2016)	°	+61.12472508469	Gaia DR3 ^d	
R.A. proper motion, μ_{RA}	mas yr ⁻¹	-68.298 ± 0.085	Gaia DR3 ^d	
decl. proper motion, μ_{decl}	mas yr ⁻¹	169.435 ± 0.097	Gaia DR3 ^d	
Parallax, ϖ	mas	52.9017 ± 0.1037	Gaia DR3 ^d	
Distance, d	pc	18.896 ± 0.034	Bailer-Jones Catalog ^e	
$B - V$ color	mag	0.534 ± 0.031	TIC v8.2 ^a	
Johnson B magnitude	mag	5.328 ± 0.021	TIC v8.2 ^a	
Johnson V magnitude	mag	4.794 ± 0.023	TIC v8.2 ^a	
Gaia G magnitude	mag	4.650 ± 0.003	TIC v8.2 ^a	
TESS magnitude	mag	4.268 ± 0.007	TIC v8.2 ^a	
2MASS J magnitude	mag	3.936 ± 0.250	TIC v8.2 ^a	
2MASS H magnitude	mag	3.681 ± 0.222	TIC v8.2 ^a	
2MASS K_s magnitude	mag	3.638 ± 0.254	TIC v8.2 ^a	
WISE W_1 magnitude	mag	3.474 ± 0.422	TIC v8.2 ^a	
WISE W_2 magnitude	mag	3.183 ± 0.293	TIC v8.2 ^a	
WISE W_3 magnitude	mag	3.497 ± 0.014	TIC v8.2 ^a	
WISE W_4 magnitude	mag	3.443 ± 0.023	TIC v8.2 ^a	
T_{eff}	K	6045 ± 100	SpecMatch–Synthetic ^f	✓
T_{eff}	K	5997 ± 110	SpecMatch–Empirical ^g	
T_{eff}	K	6100 ⁺⁵⁹ ₋₇₂	SED (§5.3)	
T_{eff}	K	6114 ⁺¹⁵⁹ ₋₁₃₀	TIC v8.2 ^a	
T_{eff}	K	6184 ± 85	Ramírez et al. (2012)	
T_{eff}	K	6235 ± 100	Luck and Heiter (2006)	
log g	log(cm s ⁻²)	4.1 ± 0.1	SpecMatch–Synthetic ^f	✓
log g	log(cm s ⁻²)	4.04 ± 0.08	SED (§5.3)	
log g	log(cm s ⁻²)	4.05 ^{+0.08} _{-0.10}	TIC v8.2 ^a	
log g	log(cm s ⁻²)	4.07 ± 0.04	Ramírez et al. (2012)	
log g	log(cm s ⁻²)	4.43 ± 0.1	Luck and Heiter (2006)	
$M_{\star}$	$M_{\odot}$	1.25 ± 0.06	SpecMatch–Synthetic ^f	
$M_{\star}$	$M_{\odot}$	1.15 ^{+0.24} _{-0.20}	SED (§5.3)	✓
$M_{\star}$	$M_{\odot}$	1.15 ^{+0.21} _{-0.12}	TIC v8.2 ^a	
$M_{\star}$	$M_{\odot}$	1.29 ^{+0.02} _{-0.07}	Ramírez et al. (2012)	
$R_{\star}$	$R_{\odot}$	1.67 ± 0.04	SpecMatch–Synthetic ^f	
$R_{\star}$	$R_{\odot}$	1.70 ± 0.04	SED (§5.3)	✓
$R_{\star}$	$R_{\odot}$	1.69 ^{+0.06} _{-0.12}	TIC v8.2 ^a	
$L_{\star}$	$L_{\odot}$	3.59 ± 0.23	SED (§5.3)	✓
$L_{\star}$	$L_{\odot}$	3.58 ^{+0.13} _{-0.09}	TIC v8.2 ^a	
[Fe/H]	dex	0.11 ± 0.06	SpecMatch–Synthetic ^f	✓
[Fe/H]	dex	0.03 ± 0.09	SpecMatch–Empirical ^g	
[Fe/H]	dex	0.09 ± 0.05	SED (§5.3)	
[Fe/H]	dex	0.097 ± 0.016	TIC v8.2 ^a	
[Fe/H]	dex	0.06 ± 0.06	Ramírez et al. (2012)	
[Fe/H]	dex	0.07 ± 0.05	Luck and Heiter (2006)	
$v \sin i$	km s ⁻¹	5.2 ± 1.0	SpecMatch–Synthetic ^f	✓
$v \sin i$	km s ⁻¹	8.1	Luck (2017)	
$v \sin i$	km s ⁻¹	< 25	Slettebak (1955)	
$P_{\text{rot}}/\sin i$	d	16.5 ± 3.2	Calculated using $v \sin i$ and $R_{\star}$	

P_{rot}	d	$4.13^{+0.23}_{-0.19}$	GP (§5.3)	✓
$\langle S \rangle$		0.1337 ± 0.0003	APF/Levy	
$\langle S \rangle$		0.128 ± 0.001	Keck/HIRES	
$\log \langle R'_{HK} \rangle$		-5.101 ± 0.003	APF/Levy	
$\log \langle R'_{HK} \rangle$		-5.16 ± 0.01	Keck/HIRES	
Age	Gyr	$7.8^{+3.2}_{-3.1}$	BAFFLES ^h	
Age	Gyr	$2.9^{+2.2}_{-0.8}$	Isochrone (§5.3)	
Age	Gyr	$3.5^{+1.3}_{-0.3}$	Isochrone (Ramírez et al. 2012)	
Age	Gyr	4.80 ± 1.17	Isochrone (Luck 2017)	
Age	Gyr	8.4 ± 4.9	Empirical relation ⁱ	

^a TESS Input Catalog (TIC) version 8.2 (Paegert et al. 2022).

^b The Hipparcos and Tycho Catalogs (ESA 1997).

^c The Bright Star Catalog, 5th Revised Edition (Hoffleit and Jaschek 1991).

^d Gaia Data Release 3 (DR3; Gaia Collaboration et al. 2023).

^e Median of the geometric parallax posterior (Bailer-Jones et al. 2021).

^f SpecMatch-Synthetic (Petigura et al. 2017) applied to APF/Levy data.

^g SpecMatch-Empirical (Yee et al. 2017) applied to archival Keck/HIRES data (Butler et al. 2017).

^h Bayesian Ages For Field LowEr-mass Stars (BAFFLES; Stanford-Moore et al. 2020).

ⁱ Empirical R'_{HK} -Age relation (Mamajek and Hillenbrand 2008).

Table 5.1: HD 5015 Stellar Properties.

resulting posterior distributions from each fit are then weighted by the Bayesian evidence of the corresponding model and averaged together to estimate the best-fit stellar parameters.

We used photometry from TIC v8.2 (Paegert et al. 2022), including ground BV magnitudes, Gaia G magnitude, TESS magnitude, 2MASS JHK_s magnitudes, and WISE W_1 and W_2 magnitudes (note that the WISE W_3 and W_4 magnitudes are not considered by ARIADNE), together spanning 0.4–5 μm . Because HD 5015 is nearby at only $d = 18.896 \pm 0.034$ pc (Bailer-Jones et al. 2021), we fixed the extinction parameter to $A_V = 0$ in our fit. The stellar effective temperature, surface gravity, and metallicity were allowed to vary with normal priors informed by our spectroscopy analysis. The effective temperature was centered at 6045 K with $\sigma = 100$ K, surface gravity was centered around 4.05 (cgs units) with $\sigma = 0.1$, and metallicity was centered around 0.11 dex with $\sigma = 0.06$. The resulting BMA posterior medians and 68% confidence intervals are $T_{\text{eff}} = 6100^{+59}_{-72}$ K, $\log g = 4.04 \pm 0.08$, and $[\text{Fe}/\text{H}] = 0.09 \pm 0.05$. ARIADNE internally computes the bolometric flux at Earth by integrating the best-fit SED model ($F_{\text{bol}} = 3.2 \pm 0.1 \times 10^{-7}$ erg s $^{-1}$ cm $^{-2}$), then uses the Gaia parallax to convert this to a bolometric luminosity ($L_{\text{bol}} = 3.59 \pm 0.23 L_{\odot}$). The Stefan–Boltzmann relation then gives the stellar radius ($R_{\star} = 1.70 \pm 0.04 R_{\odot}$), which can be combined with $\log g$ to give the stellar mass ($M_{\star} = 1.15^{+0.24}_{-0.20} M_{\odot}$). These values are consistent with the spectroscopically derived parameters and the TIC v8.2 values (Paegert et al. 2022) that are listed in Table 5.1. The broadband photometry and best-fit SED model are shown in Figure 5.1.

Stellar Rotation

The TESS light curve of HD 5015 shows clear signs of quasi-periodic variability indicative of rotationally-modulated starspots, as shown in Figure 5.3. We ruled out potential contaminating sources in the TESS aperture by comparing the sector 24 Target Pixel File (Figure 5.2) to nearby

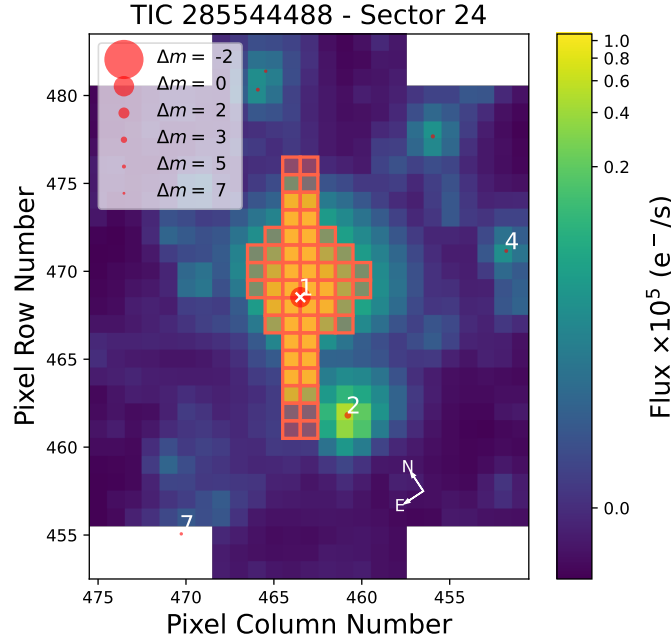


Figure 5.2: Sector 24 TESS Target Pixel File of HD 5015 (TIC 285544488) with the SPOC pipeline aperture overlaid in red. HD 5015 is shown by the white “x” in the center of the frame and labeled as target 1. Nearby sources from Gaia DR3 (Gaia Collaboration et al. 2023) are shown as red circles with radii scaled by the magnitude difference with the target star. This figure was created with `tpfplotter` (Aller et al. 2020).

sources crossmatched in Gaia DR3 (Gaia Collaboration et al. 2023). We found no bright Gaia sources that would cause significant aperture contamination—the nearest Gaia source is approximately 5 magnitudes dimmer than HD 5015. Then, using the normalized two-minute cadence PD-CSAP flux, we computed the generalized Lomb–Scargle (LS) periodogram (Lomb 1976; Scargle 1982) for each individual sector of TESS data. We found significant peaks in the LS periodograms in the range of 3–10 days, shown for the 6 TESS sectors in Figure 5.4. However, due to the effects of differential stellar rotation and the stochastic nature of starspot evolution (e.g., Dumusque et al. 2011b), these peaks are not always well defined and significant LS power can be found in lower peaks between about 3–10 days.

Therefore, to further quantify the stellar rotation period, we modeled the TESS light curve using a Gaussian process (GP) regression (Rasmussen and Williams 2006). It has been shown that the light curve of a rotating star can be well approximated with a GP kernel consisting of a mixture of two stochastically-driven simple harmonic oscillator (SHO) terms separated by a factor of 2 in frequency (e.g., Angus et al. 2018). We constructed a one-dimensional GP model using the `RotationTerm` implementation of the SHO mixture kernel from the `celerite2` package (Foreman-Mackey et al. 2017; Foreman-Mackey 2018), then solved for the maximum a posteriori (MAP) GP hyperparameters using the `exoplanet` package (Foreman-Mackey et al. 2021a,b). The full posterior distributions for the GP hyperparameters were then sampled using the Hamiltonian

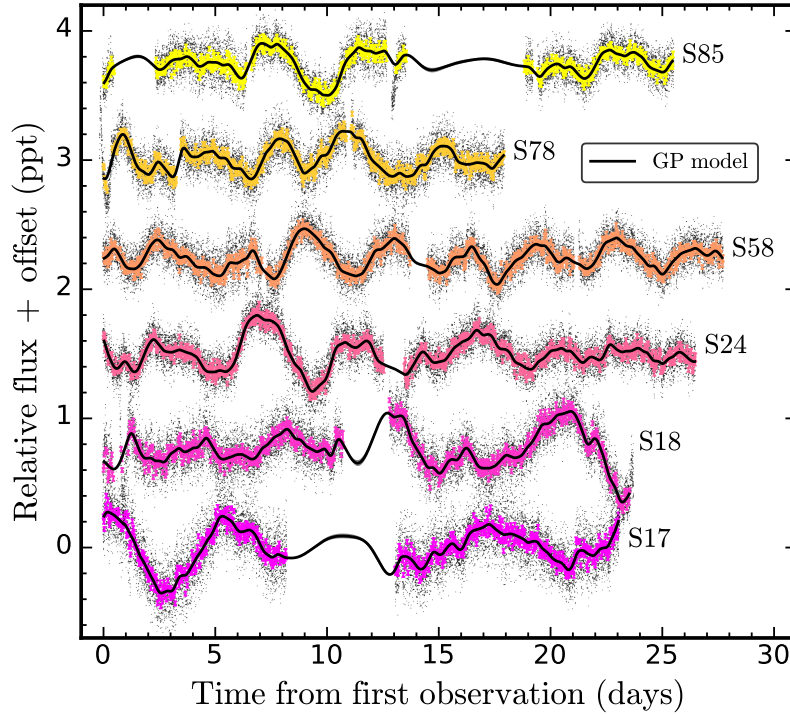


Figure 5.3: TESS light curve and stellar rotation GP model for HD 5015. The black points show the normalized two-minute cadence PDCSAP flux measurements with a constant arbitrary offset. The colored points with error bars have been binned to 0.5 hr intervals, and the black line shows the best-fit median GP model described in Section 5.3.

Monte Carlo (HMC) No-U-Turn Sampler (NUTS) implemented in PyMC (Hoffman and Gelman 2014; Salvatier et al. 2016). We assumed conservative priors on the hyperparameter informed by the MAP fit values, and an initial stellar rotation period set by the peak of the LS periodogram of the full TESS light curve. We ran the HMC using 4 chains with 10,000 steps per chain and a burn-in of 5,000 steps. Convergence was assessed by checking that the Gelman–Rubin statistic was equal to 1 (Gelman and Rubin 1992).

The final posterior median GP model is shown in Figure 5.3 with the TESS photometry, and the marginalized GP posterior distribution for the stellar rotation period is compared to the per-sector LS periodograms in Figure 5.4. From the marginalized posterior median and 68% confidence interval, we determine a stellar rotation period of $P_{\text{rot}} = 4.13^{+0.23}_{-0.19}$ days. To check for consistency and rule out the possibility that a single TESS sector was dominating the signal, we performed a leave-one-out analysis by rerunning the HMC a total of 6 additional times, removing one sector of sector in each run. The resulting posterior values ranged from $3.83^{+0.20}_{-0.18}$ days to $4.35^{+0.30}_{-0.25}$ days, which are consistent with the full posterior median to 1σ . However, we note that the reported period uncertainties may still be underestimated due to astrophysical systematics such as starspot evolution and differential rotation. The stellar rotation period from the GP analysis is consistent

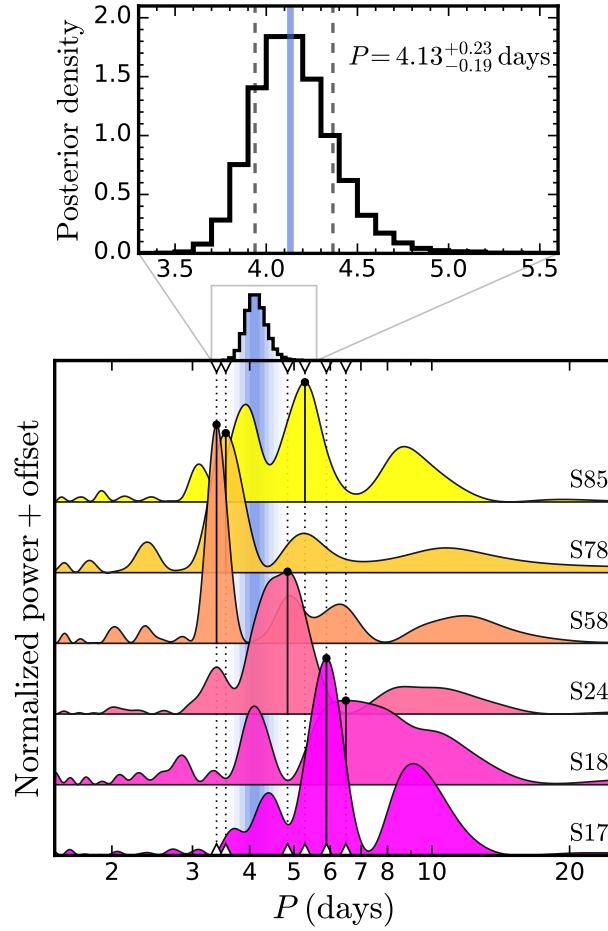


Figure 5.4: Top: Marginalized posterior probability distribution of the stellar rotation period from the TESS light curve GP analysis. The vertical blue line shows the distribution median and the dashed vertical lines show the 68% confidence interval. Bottom: Normalized and offset Lomb–Scargle periodograms of individual sectors of TESS photometry. The period at maximum power is indicated by a vertical black line for each sector. The GP posterior is overlaid in blue for comparison.

with the maximum rotation period determined by $v \sin i$ and the stellar radius ($P_{\text{rot}}/\sin i = 16.5 \pm 3.2$ days).

While the TESS residuals do not show obvious signs of deep transits, we note that we have not yet conducted a thorough search for potential transit signals in TESS photometry. In future work, we will further analyze the TESS data by performing a Box Least Squares (BLS) search for transits (Kovács et al. 2002). We will also inject synthetic transit signals into the TESS residuals and attempt to recover them using BLS in order to quantify the range of planet radii and orbital periods that can be ruled out. Note that no transiting planets or planet candidates have yet been reported in the literature for the HD 5015 system.

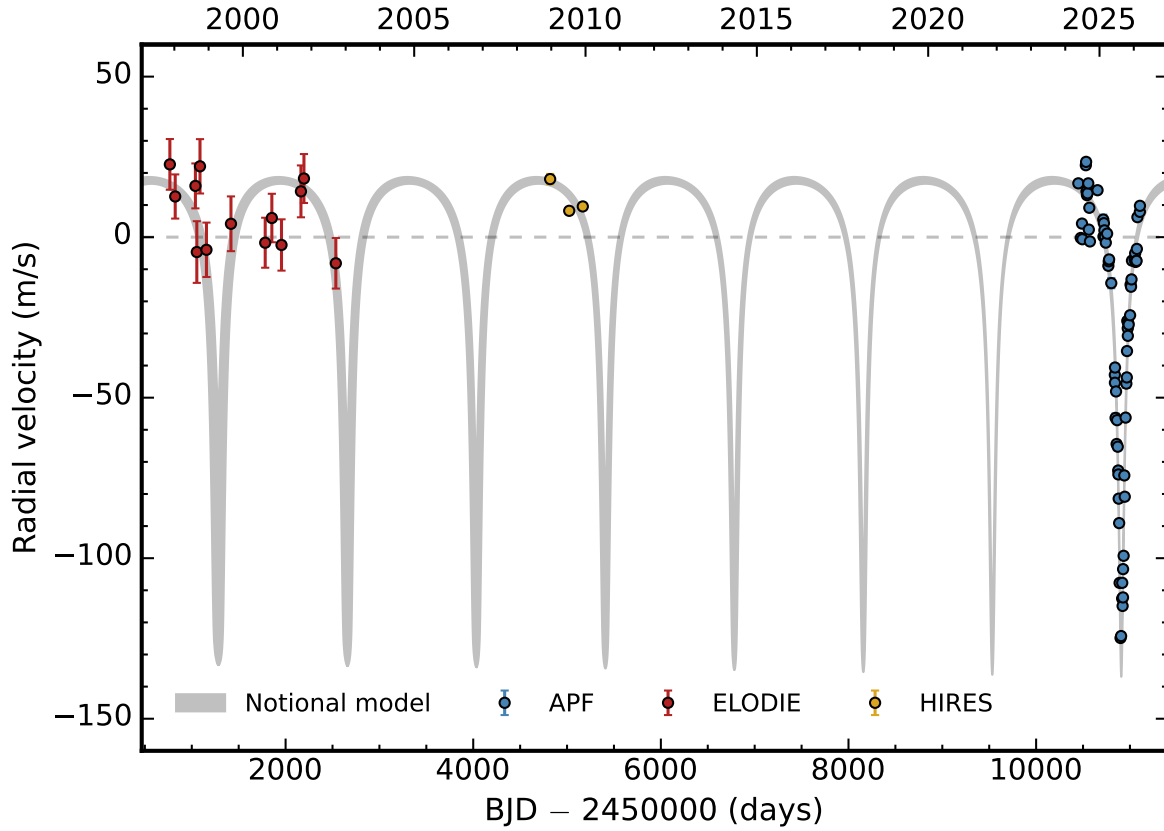


Figure 5.5: RV timeseries observations of HD 5015 from APF/Levy (blue) and archival data from OHP/ELODIE (red), and Keck/HIRES (yellow). An example of one realization of single-planet Keplerian model is shown in gray. The error bars show the individual measurement uncertainties, which range from $0.5\text{--}1.5\text{ m s}^{-1}$ (APF), $7\text{--}10\text{ m s}^{-1}$ (ELODIE), and $0.5\text{--}1.5\text{ m s}^{-1}$ (HIRES). All data have been binned to 12 hr intervals. The notional Keplerian model is one of many possible orbital solutions that could be consistent with the data.

5.4 Preliminary Radial Velocity Analysis

The 71 nights of RVs from APF/Levy, 13 nights of archival RVs from OHP/ELODIE, and 3 nights of archival RVs from Keck/HIRES are plotted in Figure 5.5. In total, the RV observations span 28.3 yr from 1997 to 2026. We began by analyzing the APF data alone, largely in part due to the lack of significant RV variations in the ELODIE observations and the sparsity of the HIRES data. The APF observations began 2024 May and started to show signs of a decreasing RV trend in 2025 February. This trend continued until around 2025 August when the RVs reached their minimum value ($\Delta\text{RV} \approx -140\text{ m s}^{-1}$) and the trend started to reverse. As of 2026 May, the RVs appear to have increased back to about the same value as when observations started. Overall, the trend appears to be well described by a Keplerian orbit whose period is, at minimum, the duration of the

APF observations (~ 2 years). However, because the RV observations do not span a continuous full of the orbit, the exact orbital period (and hence the minimum mass of the perturber) cannot be readily measured. Here, we attempt to constrain plausible Keplerian orbit solutions that are consistent with the available data and search for additional shorter-period signals. Our goal in future work is to measure a more precise period once additional observations are obtained.

Provisional Period Search

RVSearch Analysis

We began our analysis by systematically comparing Keplerian orbit models with different periods to the RV observations of HD 5015. We used the RVSearch package (Rosenthal et al. 2021), which uses an iterative search algorithm built on top of the RadVel code (Fulton et al. 2018) to identify periodic RV signals and fit Keplerian models. In brief, RVSearch constructs a likelihood model from the observed RVs, an n -planet Keplerian model, RV jitter terms, and instrumental velocity offsets. As a fiducial model, RVSearch fits either a linear or quadratic trend to the data if the Bayesian information criterion (BIC) results in a $\Delta\text{BIC} \geq 5$ compared to a simpler (flat line) fit. The BIC is defined as $\text{BIC} = -2\ln(\mathcal{L}) + k\ln(N)$ where $\mathcal{L}$ is the model likelihood, k is the number of free parameters in the model, and N is the number of observations. Then, RVSearch constructs a goodness-of-fit periodogram by stepping through a fixed period grid and computing the ΔBIC between the best-fit sinusoid model and the fiducial model. For any periodogram peaks that exceed a predefined false alarm probability (here defined as 0.1%) a MAP optimization of the Keplerian model is performed. This n -planet model (plus any trend terms) then becomes the new baseline model for the next search iteration, which repeats this process using a Keplerian model with $n + 1$ planets for the ΔBIC comparison. For a more detailed summary of RVSearch, see Rosenthal et al. (2021) or Chapter 4.

We binned all RVs to nightly intervals, then ran RVSearch with a minimum search period of 3 days and a maximum search period constrained by the total baseline of the RV observations (1.7 yr for APF only, or 28.3 yr including ELODIE). Using only the APF/Levy observations, RVSearch returned a highly significant peak at 569 days, with a significant secondary peak at roughly half this period. The MAP fit for this signal resulted in a best-fit orbital period of $P = 660$ days, very close to the 656.6 day baseline of the APF data. The 660 day period is therefore the minimum orbital period for the object orbiting HD 5015 creating the the large RV variation in the APF data. After adding a second Keplerian to the model, RVSearch did not return any additional significant signals, indicating that no other potential companions are detectable in the data set. The single-planet ΔBIC periodogram from RVSearch is shown in Figure 5.6.

We repeated the ΔBIC periodogram analysis including both APF and ELODIE and found a very similar result. The main differences between this run and the APF-only result were a noisier periodogram and a peak period that is less statistically significant. In the MAP fit, the ELODIE data have highly inflated error bars and do not appear to be well approximated by the model, indicating that the lower peak significance is likely driven by sinusoid approximation and treatment of instrumental jitter by RVSearch rather than actual constraints from the ELODIE data. We did

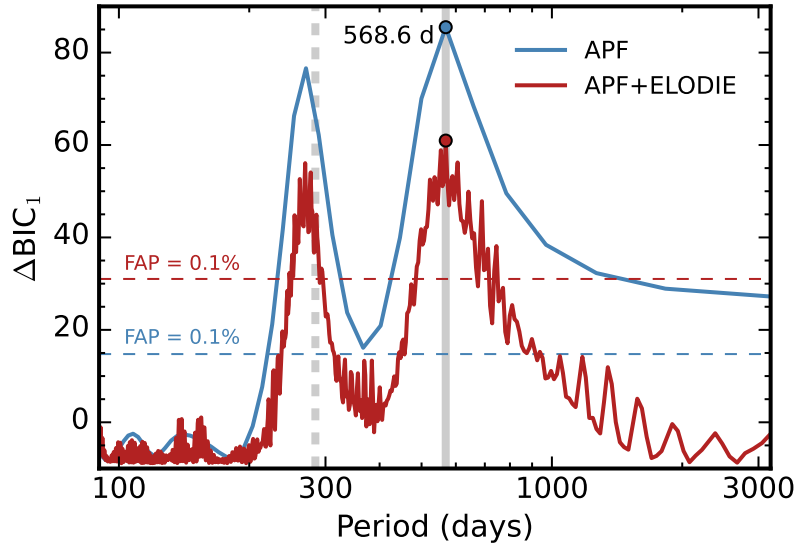


Figure 5.6: ΔBIC_1 periodograms of the RVs for HD 5015 computed with a single-planet model in RVSearch. The blue line shows the periodogram computed using only the APF observations, while the red line shows a periodogram that also included the ELODIE data. The corresponding false alarm probability (FAP) thresholds are shown by horizontal dashed lines. The peak of the periodogram occurs at a period of about 569 days, with a lesser peak at approximately half this period (vertical dashed gray line). The HIRES RVs were omitted from this analysis because only 3 nights of observations were available.

not include the archival HIRES data in this portion of the analysis because of the limited amount of data.

Chi-Squared Periodogram Analysis

The $P = 660.7$ day model obtained above is likely incorrect due to its proximity to the observational baseline and limited phase coverage of the RV observations. Because of the long-period nature of the signal, multiple longer periods may be consistent with the observations if the eccentricity is also increased. These possible longer periods may be constrained by the archival RV data from ELODIE and HIRES given that those observations do not show any indication of the large eccentric signal in the APF data.

To explore which orbital periods could be consistent with the available observations of HD 5015, we first computed a grid of single-planet Keplerian models over a fixed period grid ranging from 500 days to 20,000 days. Unlike RVSearch, each fixed-period model was fit to the data with all other parameters free, including eccentricity. We then constructed a periodogram based on the reduced chi-squared statistic (χ^2_ν) from each fit. Though significantly more computationally expensive than the RVSearch algorithm, this analysis allowed us to visualize the degree of consistency between the data and full Keplerian models over a wide range of orbital periods.

To do this, we used `exoplanet` (Foreman-Mackey et al. 2021a) to construct a single-planet Keplerian orbit model with fixed orbital period. The parameters K and T_0 were assigned conservative priors informed by the `RVSearch` results, and $\sqrt{e} \cos \omega$ and $\sqrt{e} \sin \omega$ were assigned uniform priors. The MAP parameters were then determined for each fixed-period model using the `pymc-ext`⁶ optimization routine.

For each model, we computed the reduced chi-squared statistic (χ_v^2) as

$$\chi_v^2 = \frac{1}{\nu} \sum_i^{n_{\text{tel}}} \sum_j^{n_{\text{obs}}} \left(\frac{y_{ij} - m(t_{ij}) - \gamma_i}{\sigma_{y,ij}} \right)^2, \quad (5.1)$$

where y_{ij} is the j th RV measurements from the i th instrument, $\sigma_{y,ij}$ is the corresponding measurement uncertainty, $m(t_{ij})$ is the RV model calculated at the t_{ij} timestamp, γ_i is the instrumental offset for the i th instrument, and ν is the number of degrees of freedom given by subtracting the number of free model parameters from the total number of observations. We then converted each χ_v^2 value to a periodogram power as a function of frequency f (where $f = 1/P$) as

$$\mathcal{P}(f) = \sqrt{\exp[-\ln \chi_v^2(f)]}. \quad (5.2)$$

We computed $\mathcal{P}(f)$ over a grid of 500 points spaced uniformly in log space between periods of 500–20,000 days for three different RV data sets consisting of: (1) APF only; (2) APF and ELODIE; and (3) APF, ELODIE, and HIRES. The resulting χ^2 periodogram (Figure 5.7) reveals “islands” of possible orbital solutions that are consistent with all three data sets, with each island spaced roughly uniformly in linear period space. The periodogram absolute maximum occurs at $P = 1070$ days, but the ~ 660 day signal identified by `RVSearch` also appears as a local maximum at a value roughly $5/8$ the absolute maximum. The chi-squared periodograms for all three data sets are shown in panel (a) of Figure 5.7. To illustrate how models with different combinations of P and e are consistent with the RV observations, we show several examples of orbit fits plotted over the APF data in panel (b) of Figure 5.7. In future work, we will experiment with increasing the number of grid points to values greater than 500 to improve our confidence in the χ^2 periodogram results. This preliminary analysis emphasizes that current observations are insufficient to fully constrain the orbit of the perturber.

Nested Sampling

To further quantify potential orbital periods that are consistent with the current data, we use nested sampling to sample the posterior distribution over a wide period space. Nested sampling is a technique developed to directly estimate Bayesian evidence for a given likelihood function and set of priors, but fortuitously generates posterior samples as a byproduct (Skilling 2004, 2006). Notably, nested sampling is particularly well suited for sampling multimodal distributions, as we have here. `juliet` is a fast and versatile open-source Python package⁷ that can model an assortment of exoplanet observations, including RVs (Espinoza et al. 2019). The RV module of `juliet` is a wrapper

⁶<https://github.com/exoplanet-dev/pymc-ext>

⁷<https://github.com/nespinoza/juliet>

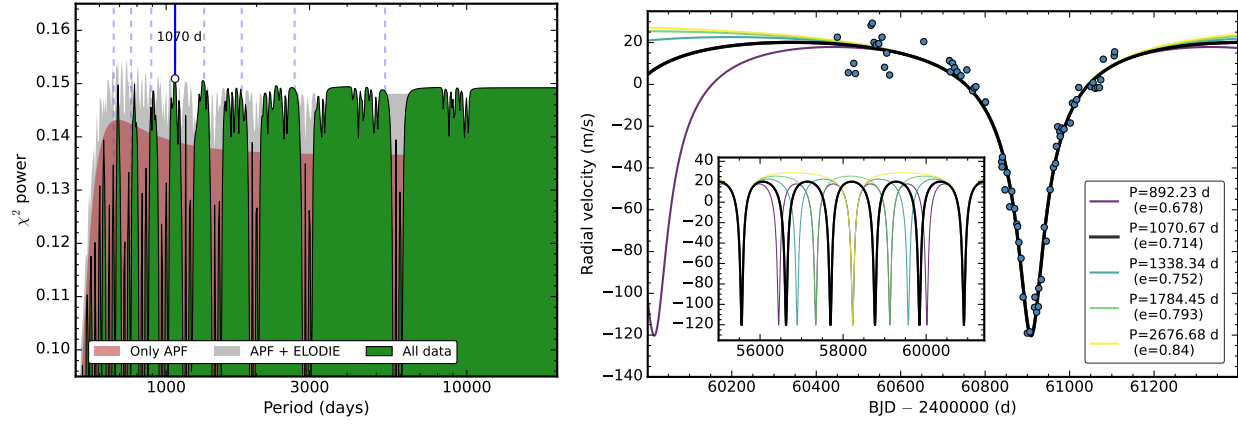


Figure 5.7: Chi-squared periodograms (a) and example orbit fits that are compatible with the existing RV observations (b). The periodograms were computed using three separate data sets consisting of APF only (red); APF and ELODIE (gray); and APF, ELODIE, and HIRES (green). The lack of significant RV variations in the ELODIE and HIRES data constrain plausible orbital periods to roughly uniformly-spaced regions of low χ^2 . The absolute maximum of the periodogram is labeled at $P_0 = 1070$ days, and vertical dashed lines show periods of $5P_0/n$ where $n \in \{1, 2, 3, 4, 5, 6, 7, 8\}$. The corresponding orbit models (each with a different eccentricity) are shown in panel (b) with the APF data (blue circles). The inset plot shows a zoom out of the same orbit models.

built around *RadVel* (Fulton et al. 2018) that uses *MultiNest*⁸ to perform nested sampling (Feroz et al. 2009; Buchner et al. 2014).

We set up *juliet* with a wide uniform prior for the orbital period between 300 and 3000 days, overlapping with several peaks in the χ^2 periodogram. We selected uniform priors between -1 and $+1$ for $\sqrt{e}\cos\omega$ and $\sqrt{e}\sin\omega$ and conservative normal priors based on the MAP parameters from *RVSearch* for the time of conjunction, $\pi(T_0 - 2450000) = \mathcal{N}(6739.0, 50.0)$, and RV semi-amplitude, $\pi(K) = \mathcal{N}(70.0, 20.0)$. Instrumental offset and jitter terms were assigned normal priors centered around the mean per-instrument RV and uncertainty, respectively, with standard deviations of 100 m s^{-1} and 10 m s^{-1} . We ran a total of three *juliet* models, each with 2000 live points, using (1) the APF data only; (2) APF and ELODIE; and (3) APF, ELODIE, and HIRES. The resulting posterior distributions for the orbital period and eccentricity are shown in Figure 5.8.

Interestingly, the model using only the APF data has a relatively wide period posterior centered at about 2059 days with a 68% confidence interval of ± 17 days, many σ away from both the *RVSearch* and χ^2 periodogram periods. With this period, the precise shape of the RV curve measured by APF yields an eccentricity of 0.8. Adding the ELODIE data to the analysis splits the posterior distribution into two modes: one weaker mode centered at a period of 2059 days and another stronger mode at 1372 days. Because of the shorter orbital period of the stronger mode, the corresponding eccentricity must be smaller ($e \approx 0.75$) in order to match the data. In this case, the ELODIE data constrain the period such that the periastron passage of the object does

⁸<https://github.com/johannesBuchner/MultiNest>

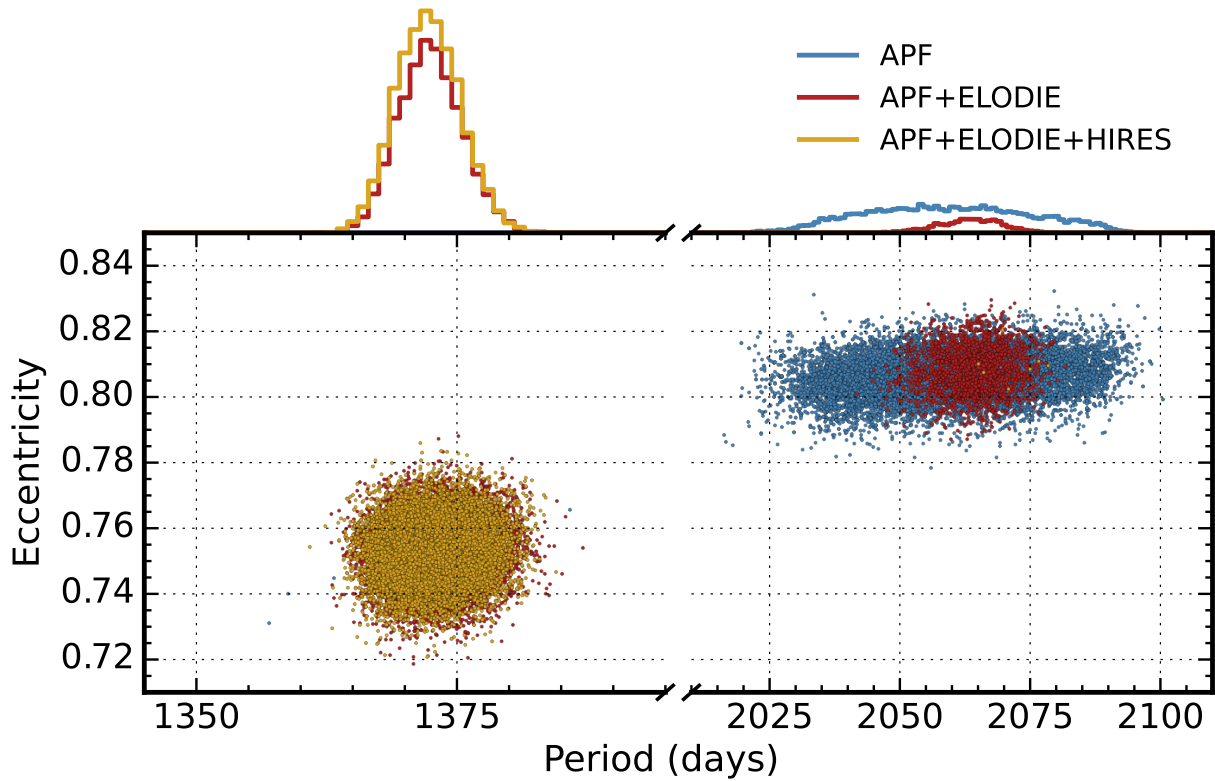


Figure 5.8: Posterior distributions of eccentricity and orbital period from the nested sampling analysis of HD 5015. Using only the APF data results in a wide period posterior (blue) centered roughly at 2059 days and an eccentricity of ~ 0.81 . Adding the ELODIE data results in a clearly bimodal posterior (red), preferring an orbital period of about 1373 days and a smaller eccentricity of ~ 0.75 , but still showing evidence for the period and eccentricity preferred by the APF-only data set. Combining APF, ELODIE, and HIRES produced a posterior (yellow) strongly preferring the shorter 1372 day period.

not coincide with the ELODIE observations (otherwise we would have seen large variations in the ELODIE RVs). Finally, the addition of the 3 HIRES observations eliminates the posterior mode at 2059 days, resulting in a well-defined unimodal distribution with $P = 1372$ days and $e = 0.753$. Although this last period appears to be preferred by the nested sampling algorithm we emphasize that this should be interpreted as only one of many possible orbital scenarios that are consistent with the available RV observations of HD 5015. For the purpose of demonstration, a Keplerian model with these parameters is shown with the RV observations in Figure 5.5, and a phase-folded version of the model and data are presented in Figure 5.9.

In future work, we will expand this analysis by including additional nested sampling trials experimenting with different prior assumptions. Specifically, our current choice of Gaussian priors may bias the sampling algorithm to prefer models in which the ELODIE and HIRES RVs are similar to the flat portions of the APF RVs, given the size of the ELODIE error bars and the

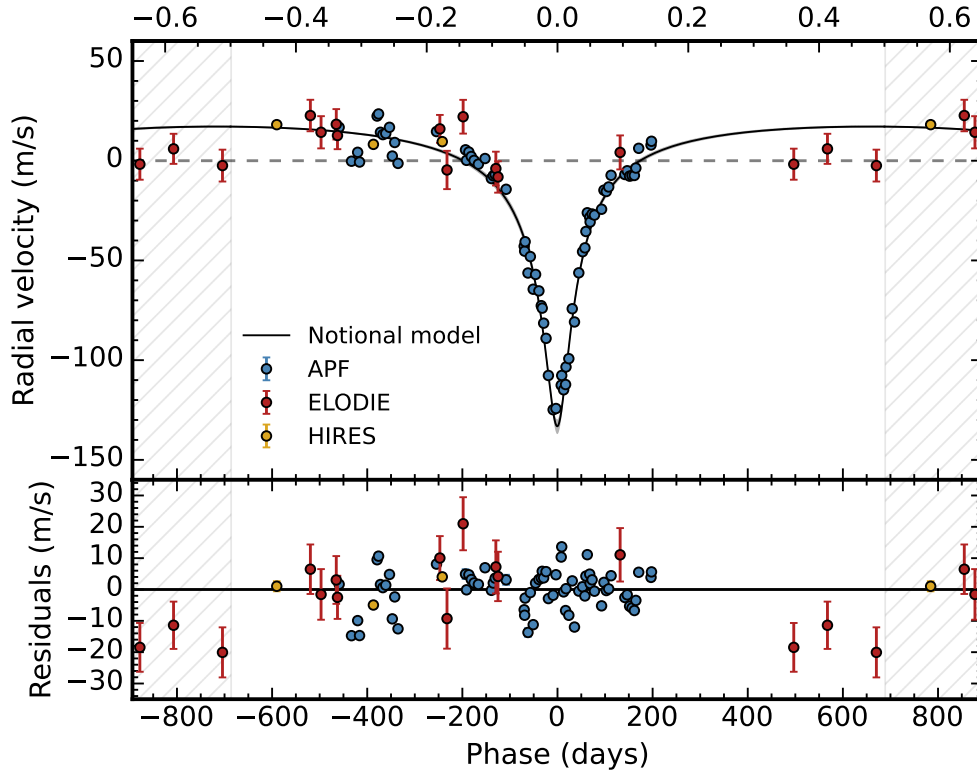


Figure 5.9: Top: RVs phase-folded to a period of 1375 days. The notional RV model from Figure 5.5 is shown in black, while observations binned to nightly intervals are shown as circles with error bars corresponding to the measurement uncertainties. Bottom: RV residuals after subtracting off the calculated values from the example model.

amplitude of the RV change seen in the APF data. Our future analysis will include scenarios with uniform priors in which the ELODIE and HIRES data are significantly offset from the flatter APF data. Understanding how the best-fit period(s) may change with different prior choices will increase our confidence in these results. However, in an ideal scenario, future observations would provide sufficient phase coverage of a full orbit in order to robustly constrain the orbital period and properties of the perturber.

Stellar Activity Analysis

We analyzed the stellar activity measurements from APF/Levy to search for activity signals and rule out a potential stellar origin of potential RV signals. The APF spectral bandpass includes the Ca II H and K emission lines at wavelengths of 3968 Å and 3934 Å. The strength of emission in the line cores at these wavelengths relative to the continuum flux is known to correlate with chromospheric stellar activity, which can produce correlated noise in RV measurements that mimics planetary signals. Therefore, we quantified the stellar activity by measuring the Mount Wilson

S -index from the Ca II H and K emission lines in each spectrum used to measure the RVs (Wilson 1968; Duncan et al. 1991).

An inspection of the S -index measurements (Figure 5.10) reveals clear variations that correlate in time, and a Lomb–Scargle periodogram of the data confirms that this signal turns over with a period of about 500 days. We characterized this signal by modeling the nightly-binned S -index data with a simple sinusoid defined by a period P , amplitude A , mean S -index $\langle S \rangle$, and a reference time. We also included an extra jitter term, added in quadrature with the S -index uncertainties, in order to account for potentially underestimated measurement errors. Using this model, we defined a Gaussian likelihood function and conservative priors based on the LS periodogram results, then sampled the posterior for 10,000 steps using the HMC NUTS implemented in PyMC (Hoffman and Gelman 2014; Salvatier et al. 2016). From the converged posteriors, we then computed the median and 68% confidence intervals of the sinusoid model parameters. We find a period of $P = 502^{+13}_{-12}$ days, mean S -index value of $\langle S \rangle = 0.13458 \pm 0.00024$, and amplitude of $A = 0.00480 \pm 0.00033$. The S -index data, best-fit sinusoid model, and LS periodogram are shown in Figure 5.10 alongside the RV data for comparison.

A notable observation of Figure 5.10 is that the minimum of the RV curve appears to coincide with the minimum of the S -index data. Indeed, there is a statistically significant correlation between the RVs and S -index, with a Pearson correlation coefficient of 0.75 (and p -value $\ll 0.001$). While at first glance, this may appear to suggest that the RV signal we see is the result of stellar activity rather than a massive companion, this may not be the case. One reason is that the period of the S -index signal is well-constrained because the observations span at least one complete cycle continuously. However, we do not see a second turnover of the RVs, suggesting that the orbital period could be much longer than the observational baseline (discussed in the previous section). Assuming that the 1372 day RV period is a lower limit, this would be highly discrepant with the S -index period.

The 502 day (~ 1.4 yr) period, small amplitude, and sinusoidal nature of the S -index variations also suggest that they are not inducing the large RV signal. The S -index signal is likely caused by a magnetic cycle, which for F-type stars of similar color to HD 5015 are typically shorter (1–2 yr) and have smaller amplitudes than their solar-type G dwarf counterparts (Mittag et al. 2019a). For example, HD 16673 is a star quite similar to HD 5015. With a spectral type of F8V and $B - V = 0.524$, this star has a measured magnetic cycle of 309.4 days (Mittag et al. 2019a). HD 16673 and 5 other stars with similar properties and magnetic cycles (e.g., see Saar and Brandenburg 1999; Boro Saikia et al. 2018) are not known to exhibit RV variations similar to HD 5015. This appears to be in agreement with Wright et al. (2008), who concluded that long-term RV variations are generally not seen in the optical absorption lines of solar-type stars undergoing magnetic cycles in their analysis of the magnetic cycle and Jupiter-analog planet in the HD 154345 system. We therefore tentatively conclude that the correlation between the S -index and RV measurements of HD 5015 is most likely a coincidence. However, we will revisit this analysis in the future once more stellar activity indicator observations become available. We will also consider analyzing the S -index and RV data simultaneously in a more robust framework to disentangle the signals in each data set.

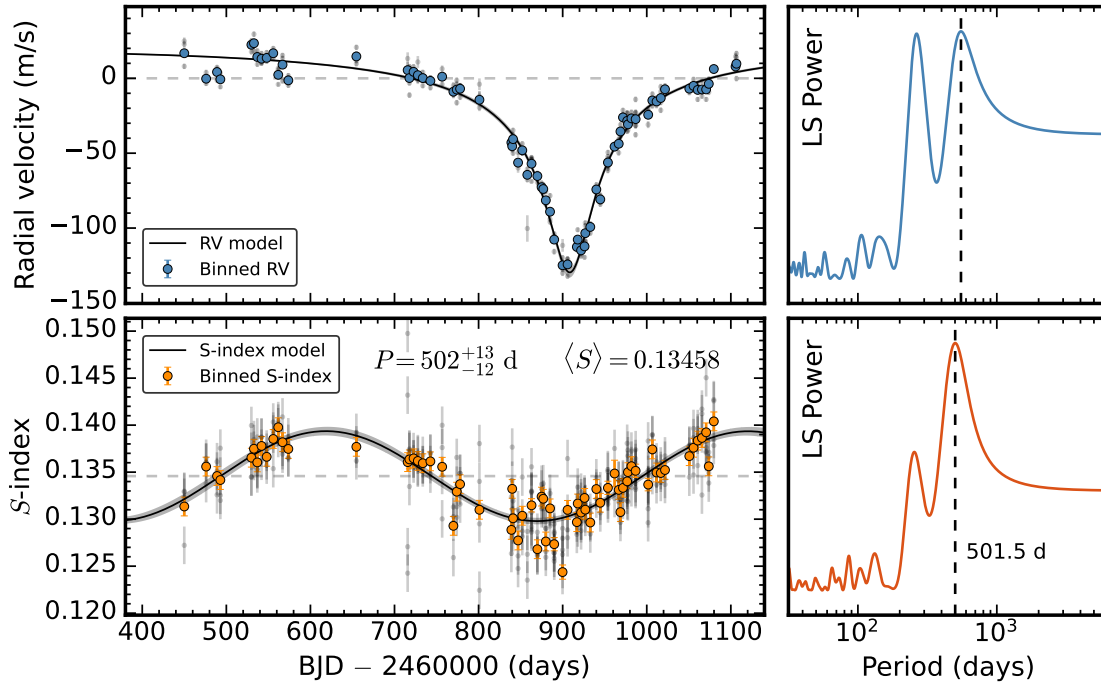


Figure 5.10: Comparison of the APF RVs and S -index data. Top: RVs from APF binned to nightly intervals (blue circles) and notional Keplerian model from Figure 5.5 (left). The individual (unbinned) measurements are shown in gray. A Lomb–Scargle periodogram of the RV data is also shown (right). Bottom: S -index values from APF and best-fit sinusoid model with 68% confidence interval (left) and LS periodogram of the S -index data (right). Binned values are shown as orange circles and individual measurements are shown in gray. The period at maximum power is indicated by the vertical dashed line.

5.5 Discussion and Future Work

The research presented in this chapter is still in the early stages. While much of the progress made thus far involves the analysis of the host star, more work remains to analyze the APF, ELODIE, and HIRES RVs to constrain the true nature of the object orbiting HD 5015 and place it into context. In this section, I provide a brief discussion of the results so far and an outline for future work investigating this fascinating system.

Additional Observations

As discussed in Section 5.4, further RV observations are required to confirm the orbital period of HD 5015’s companion and constrain the nature of this object. Ideally, an observation of a second periastron passage would be able to achieve this. However, it could be many years before we can observe another large swing in the RV signal because of its high eccentricity. Nonetheless, any future RV observations of HD 5015 will help to constrain the presence of less massive planets at

shorter orbital periods. A preliminary injection–recovery analysis of the RV residuals (Figure 5.9) suggests that the existing APF/Levy data can currently rule out planets (with circular orbits) larger than $M_p \sin i \approx 0.1 M_J$ at 0.1 au and $M_p \sin i \approx 0.5 M_J$ at 1 au. These sensitivity limits are slightly worse than the median sensitivity of the sample discussed in Chapter 4. HD 5015 is visible from Lick Observatory for most of the year, which will allow us to gradually improve these sensitivity limits to search for additional planets as more data are obtained by our continuing APF programs.

In addition to RVs, precise space-based astrometry is a complimentary detection method for systems with massive stellar or substellar companions that can constrain 3D orbital architecture and true companion masses (e.g., Venner et al. 2021). Currently, the Hipparcos–Gaia Catalog of Accelerations (HGCA; Brandt 2018, 2021) provides uniformly-reduced astrometric accelerations for over 100,000 stars from the Hipparcos mission and Gaia Early Data Release 3 (EDR3). Recently, Painter et al. (2025) reported a weakly significant (2.7σ) astrometric acceleration of HD 5015 from the HGCA with a magnitude of $3.16 \pm 0.97 \text{ m s}^{-1} \text{ yr}^{-1}$ in the sky plane. Currently, the nature of this acceleration is unknown, but it is possibly due to a giant companion (Painter et al. 2025). In the future, a joint analysis of the RVs and HGCA data may be able to better constrain the nature of the object driving the large RV variations in the APF data. Additionally, Gaia DR4 (scheduled for release in late 2026) will provide timeseries astrometry data, which will significantly improve the power of astrometry to measure companion properties.

In a future analysis, we will also investigate companion limits from existing high-contrast imaging and explore the possibility of imaging the giant companion orbiting HD 5015. To date, two epochs of high-contrast speckle imaging have been obtained in two bandpasses (562 nm and 832 nm) using the ‘Alopeke instrument on the 8 m Gemini telescope (Scott et al. 2021). These speckle observations (PI: Howell; PI: Hartman) are available on the Exoplanet Follow-up Observing Program (ExoFOP) website⁹ and demonstrate contrasts of $\Delta\text{mag} = 6.44$ (562 nm) to $\Delta\text{mag} = 6.94$ (562 nm) at an angular separation of $0''.5$. We will determine mass limits on self-luminous companions at wide orbital separations from the ‘Alopeke contrast curves in future work. HD 5015 is a mature star ($\gtrsim 2$ Gyr), so we would not expect the heat of formation to be significant for planetary-mass objects—assuming full heat redistribution and a Bond albedo similar to that of Jupiter ($A = 0.5$), the equilibrium temperature of a planetary object with $a = 2.5$ au would be $T_{\text{eq}} \approx 200$ K. Depending on the true orbital period and the phase of observation, it could be possible to directly image such an object in the mid-IR with sufficient angular resolution (e.g., with JWST and ground-based instruments). If instead the object is a star or a brown dwarf, the effective temperature would likely be much higher, potentially making direct imaging at shorter wavelengths within reach.

System Evolution

Though the orbital period of the perturber is not currently known, the shape of the RV curve indicates that its orbit is highly eccentric. Planets with very high eccentricities are relatively rare (for

⁹<https://exofop.ipac.caltech.edu/tess/>

example we currently know of only 40 substellar objects¹⁰ with eccentricities > 0.75). It would therefore be interesting to investigate possible evolutionary histories for this system once we have a better understanding of the nature of HD 5015’s companion. In a future analysis, we will investigate how the object orbiting HD 5015 fits in with the small population of highly eccentric companions. We will also investigate potential implications for eccentricity distribution of giant planets, which can provide clues to their dynamical histories and formation processes (e.g., Blunt et al. 2026). If future observations of the system reveal additional companions, it would also be interesting to understand how perturbations could have excited the orbit of the object identified here to such high eccentricity (e.g., Li et al. 2014; Blunt et al. 2019).

Habitable Zone Viability

The potential detection of an eccentric companion in this system could have important consequences for the long-term stability of any potential Earth-like worlds in this star’s HZ. Given its stellar properties (Table 5.1), the HZ of HD 5015 lies between separations of about 1.8–3.1 au for the conservative HZ and 1.4–3.3 au for the optimistic HZ (Kopparapu et al. 2013, 2014). Taking the notional orbit model with $P = 1372$, the companion would have a periastron distance of 0.61 au and an apastron distance at about 4.5 au. Such an object would therefore cross the entire HZ over a complete orbit. We are currently running a series of REBOUND N -body simulations (Rein and Liu 2012) based on the lower period limit to test whether any hypothetical Earth-mass planets could have stable orbits in the presence of such an eccentric companion. The fidelity of these simulations will need to be reassessed once additional observations of the system are obtained and we have a more robust understanding of the orbit and nature of HD 5015’s companion. However, even if the object has a longer orbital period and higher eccentricity, the HZ of this system risks being unstable to any potentially habitable worlds.

¹⁰From the NASA Exoplanet Archive, accessed 14 May 2026 (Christiansen et al. 2025).

Chapter 6

Concluding Remarks

In this dissertation, I have presented new research exploring future avenues for discovering potentially Earth-like worlds orbiting Sun-like stars. Here, I recap the main results from this work and briefly summarize recent studies that have since come out which are complimentary to the results presented in the preceding chapters. I also describe additional research performed during my Ph.D. that was not discussed elsewhere in this dissertation. Finally, I discuss future directions of the field that are relevant to this work.

6.1 Summary and Updates

The HIP 41378 System

In Chapter 2, I showed that moons orbiting the temperate giant planet HIP 41378 f would be long-term stable in the presence of tides from the host planet and gravitational perturbations from sibling planets in the system. Although current photometric observations of HIP 41378 f are not precise enough to detect exomoons, this system would be an interesting testbed for future investigations of temperate and potentially habitable exomoons. Since the conclusion of the work presented in Chapter 2, multiple additional studies of HIP 41378 have been published, primarily focused on better constraining the architecture of this multiplanet system. Based on photometry observations from CHEOPS (the CHAracterising ExOPlanet Satellite; Benz et al. 2021), a nondetection of a transit of planet d suggested that the predicted period of $P_d = 278.36$ days may be incorrect or that large transit timing variations (TTVs) of ~ 22 hr could be present (Sulis et al. 2024). Further monitoring by TESS and CHEOPS and new dynamical TTV modeling have also confirmed the presence of a sixth, non-transiting planet with an orbital period of 64 days and a mass of about $7 M_{\oplus}$, while also constraining the orbital period of planet d and highlighting the complex dynamical architecture of the system (Leonardi et al. 2025). Most recently, an additional transit of planet f was reported based on ground-based photometry from Tierras, TRAPPIST-North, and multiple Las Cumbres Observatory Global Telescope sites, leading to improved TTV and transit ephemeris constraints for planet f (García-Mejía et al. 2026). That study also ruled out a 101 day orbital

period alias for planet d, suggesting that the true orbital period is either 278, 371, or 1113 days. As our 4-body simulation in Chapter 2 showed, the overall system architecture plays an important role in determining the dynamical stability of potential moons around planet f. Therefore, narrowing down the range of possible orbital periods for each of the planets is necessary to determining plausible exomoon scenarios.

Meanwhile, other progress has been made regarding the possible ringed-planet hypothesis for HIP 41378 f. For example, Veenstra et al. (2025) published a general polarimetric model for transiting and nontransiting ringed exoplanets and suggested that HIP 41378 f should exhibit noticeable changes in the polarization of reflected light if the ring hypothesis is correct. Dynamical modeling of the system has also shown that convergent migration could capture HIP 41378 f into a spin-orbit resonance that excites the planetary obliquity to high values. Combined with a circumplanetary ring, this high obliquity could explain the large transit depth observed for planet f (Lu et al. 2025). If this scenario is correct and HIP 41378 f does in fact possess a circumplanetary ring, this could further suggest that moons exist or have existed in this system based on the ubiquity of both rings and moons around Jupiter, Saturn, Uranus, and Neptune.

A reexamination of the K2 photometry for HIP 41378 f has also constrained the planet’s spin period. Based on the K2 transit, Price et al. (2025) found that the oblateness is < 0.89 at the 95% confidence level, which is consistent with a rotation period of $P_{\text{rot}} \geq 15.3$ hr. Finally, a global spectroscopic observing effort to measure the Rossiter–McLaughlin (RM) effect during a transit of HIP 41378 f led to the first constraints on the obliquity between the stellar spin axis and the planet’s orbit (global coordination was necessary because the transit duration is 19 hr). With a measured projected obliquity of $21 \pm 8^\circ$ and a 3D spin-orbit angle of $52 \pm 6^\circ$, the potential misalignment of HIP 41378 f’s orbit with its cohort of long-period planets likely reflects a primordial tilt of the stellar spin axis relative to the protoplanetary disk, rather than dynamical interactions (Grouffal et al. 2025). This lack of past dynamical interactions would be more consistent with long-term stable moons orbiting HIP 41378 f.

Potential HWO Target Stars

In Chapter 3, I presented an analysis of stellar SEDs and a catalog of stellar properties for potential targets stars of future direct imaging searches for exoEarths. This catalog was created to inform precursor science for the Habitable Worlds Observatory (HWO), which may include obtaining additional observations of potential survey target stars or simulating spectroscopic observations of global biospheres on Earth-size planets in the HZ. Such simulations require robust stellar properties and flux measurements as input in order to make accurate predictions about what HWO could measure, which in turn drives key HWO architecture decisions such as aperture size and coronagraph inner working angle. Many studies have already expanded upon the work presented in Chapter 3. For example, the multiplicity, UV and X-ray emission, and astrometric accelerations of these potential HWO target stars have now been more thoroughly examined (González-Payo et al. 2024; Binder et al. 2024; Peacock et al. 2025; Painter et al. 2025). Other studies have also investigated the continuously habitable zones of these systems (Ware and Young 2025), the possibility of detecting exomoons around giant planets within them (Limbach et al. 2026), and whether their

HZs are dynamically viable based on the presence of known giant planets (Kane et al. 2024; Kane and Burt 2024).

Furthermore, additional target lists of potential exoEarth hosts have been created by expanding upon the 164 stars considered in this work. For example, the HWO Preliminary Input Catalog (HPIC) contains over 10,000 stars and serves as an input catalog for exoplanet yield simulations that predict how a given HWO architecture option would perform on-sky (Tuchow et al. 2024). The HWO Target Stars and Systems (TSS) working group has also created an intermediate “Tier 2” list of potential target stars that would be reasonable targets (opposed to the easiest 164 targets) for a future exoEarth imaging survey, which is based on the results of the aforementioned yield simulations (Tuchow et al. 2025). These subsequent investigations into the properties of potential HWO target stars emphasize that our knowledge of even bright, nearby stars (that in many cases have been studied extensively for decades) remains incomplete, and motivate further observational and modeling work to prepare for future exoEarth direct-imaging surveys.

Architectures of Potential ExoEarth Host Systems

Finally, in Chapter 4, I reported updated companion sensitivity limits for 120 potential HWO target stars based on over 150,000 archival RV measurements. These RV limits not only constrain the planetary architectures of these systems, which would provide astrophysical context for any future exoEarth detections, but also inform what we know about the dynamical viability of HZ planets due to the presence of massive companions. Since this work was published, additional studies have further investigated the architectures and HZ stability of potential HWO target stars. For example, in Chapter 5, I presented preliminary results on the presence of an eccentric giant companion in the HD 5015 system based on new RV data from APF. The APF program (PI: C. K. Harada) of which those data are a part continues to monitor potential HWO target stars that have not been extensively observed by previous RV surveys. Beyond this, multiple studies have since either confirmed new companions using new EPRV measurements and archival data (e.g., Beard et al. 2025; Giovinazzi et al. 2026) or placed revised upper mass limits on undetected companions in these systems (e.g., Kane et al. 2025; Li et al. 2026). These studies have continued to improve the companion detection limits derived in Chapter 4 to lower-mass planets and planets with longer orbital periods. Other studies have considered how future RV and EPRV programs could leverage information from the existing archival RVs to plan future observations with maximum efficiency to further constrain companion masses and orbits (Wittenmyer et al. 2025; Li et al. 2025). Lastly, the results of the archival RV survey have been used to inform precursor HWO studies that consider statistical methods for constraining HWO’s capacity to understand ozone onset time in exoEarths (Blunt et al. 2025) and estimate requirements for joint orbital characterization of cold giants and exoEarths with HWO (Sagynbayeva et al. 2025).

6.2 Additional Work

Throughout the process of creating this dissertation, I have contributed to a number of additional projects that have not been mentioned in the preceding chapters. My involvement in these projects included observing, conducting analyses, writing manuscripts and proposals, or otherwise participating in research collaborations.

From 2024–2025, I was an active member of NASA’s HWO Working Group for Target Stars and Systems (TSS) and a liaison for the Exoplanet Demographics working group. As a Task Lead for Catalogs & Databases within the TSS group, I collaborated with NASA personnel and members of the exoplanet community to create the TSS25 “Tier 2” list described in Tuchow et al. (2025) and assess gaps in our knowledge of the properties of potential HWO target stars. Tiers 1 and 3 are equivalent to the ExEP Mission Star List (Mamajek and Stapelfeldt 2024) and the HPIC (Tuchow et al. 2024), respectively. The work of these HWO working groups has led to numerous publications, including Peacock et al. (2025), Sagynbayeva et al. (2025), Blunt et al. (2025), and Hartman et al. (2026).

I have participated in multiple observing programs with the 3 m Shane telescope at Lick Observatory (PI: C. D. Dressing) to collect ShARCS (Shane Ao infraRed Camera–Spectrograph) adaptive optics images of potential planet-hosting stars from the TESS Input Catalog (TOI) and ExEP Mission Star List for HWO to search for unknown stellar companions in those systems. I assisted with the collection of data over several nights between 2020 and 2025. Some of these data have been included in several TESS planet discovery papers (e.g., Newton et al. 2022; Gan et al. 2022; Yee et al. 2022; Lillo-Box et al. 2023) and are will soon be published in at least one paper by Dressing et al. (submitted to AAS Journals).

Lastly, I have also participated in the TESS-Keck Survey (TKS), which was a collaboration across many institutions to use Keck/HIRES to characterize the stars, planetary masses, and architectures of potential planet-hosting stars detected by the TESS mission (Chontos et al. 2022). While I was unable to collect observations with this collaboration (in part due to COVID-19), I assisted in the characterization of four transiting sub-Neptunes orbiting the K dwarf TOI-1246 using data from TESS, Keck/HIRES, and TNG/HARPS-N (Turtelboom et al. 2022), and led the joint photometry–RV fit in the discovery of a sub-Neptune orbiting the F dwarf TOI-1751 using data from TESS, Keck/HIRES, and APF/Levy (Desai et al. 2024).

6.3 Future Directions

When this work began in 2020, a total of about 4,100 confirmed exoplanets were known¹ (Christiansen et al. 2025). Today, that number has grown by more than 50%, and is only expected to continue increasing with the continuation of TESS, JWST, and ground-based EPRV surveys, in addition to future planet-seeking missions. TESS is now entering its third extended mission and eighth year of science operations, further extending the photometric baseline for hundreds of tar-

¹<https://exoplanetarchive.ipac.caltech.edu/cgi-bin/TblView/nph-tblView?app=ExoTbls&config=PSCompPars>

gets across nearly the entire sky (especially in the continuous viewing zones near the poles) and thereby improving TESS’s sensitivity to planets orbiting faint stars, planets with small radii, and planets with orbital periods > 10 days. JWST will soon enter its fourth year of science operations and is expected to have enough fuel to continue operating into the 2040s. JWST has already led to the confirmation of at least 3 sub-stellar-mass objects (Calissendorff et al. 2023; Lagrange et al. 2025; De Furio et al. 2025) and characterized the atmospheres of at least 150 transiting planets² ranging in size from $< 1 R_{\oplus}$ to $\sim 2 R_J$, leading to better insights into planetary atmospheric structure, cloud and aerosol physics, planet formation and evolution, and potential habitability of small planets orbiting small stars (e.g., Ahrer et al. 2023; Grant et al. 2023; Greene et al. 2023; Zieba et al. 2023; Benneke et al. 2024; Gao et al. 2026). From the ground, new EPRV instruments (e.g., NEID, EXPRES, ESPRESSO, MAROON-X) will continue detecting and characterizing the masses of small planets orbiting Sun-like stars to provide updated constraints on $\eta_{\oplus}$ (e.g., Gupta et al. 2021; Brewer et al. 2020). These and other EPRV facilities (including KPF; Gibson et al. 2016) will also continue to enable demographic studies of stellar obliquities via Rossiter–McLaughlin observations to better understand how in-situ formation, high-eccentricity tidal migration, and migration through a protoplanetary disk could explain observed planetary system architectures (e.g., Rice et al. 2022; Giacalone et al. 2024; Espinoza-Retamal et al. 2024).

In the near future, the launch of NASA’s Nancy Grace Roman Space Telescope (formerly the Wide Field InfraRed Survey Telescope, or WFIRST; Green et al. 2012; Spergel et al. 2015) will unleash a flood of new exoplanet detections by leveraging the power of both transits and microlensing. With its 300-megapixel optical/NIR Wide Field Instrument (WFI), Roman will not only study dark energy and galactic bulge transients through its time-domain surveys, but will detect roughly 1,400 star-bound planets with masses $> 0.1 M_{\oplus}$ and separations $\gtrsim 1$ au via their gravitational lensing of background starlight (Penny et al. 2019). Roman will also measure the abundance and mass function of free-floating planets (FFPs) to investigate the origin and evolution of planetary systems and the formation of isolated objects via gravitational collapse. The number of FFPs that Roman is expected to detect is ~ 250 with masses $> 0.1 M_{\oplus}$ (Johnson et al. 2020). Additionally, the WFI survey will detect $\sim 60,000$ – $200,000$ transiting exoplanets, of which ~ 7000 – $12,000$ will be small planets ($< 4 R_{\oplus}$) with separations $\lesssim 0.3$ au (Montet et al. 2017; Wilson et al. 2023). Meanwhile, Roman’s second instrument, the Roman Coronagraph Instrument (CGI), will be a technology demonstration that will test new space-based starlight suppression instrumentation and detect a limited number of known giant exoplanets in reflected light (e.g., Kasdin et al. 2020; Carrión-González et al. 2021; Bailey et al. 2023; Krist et al. 2023). The Roman CGI is a critical proof-of-concept stepping stone toward the next generation of space-based coronagraphs that will be capable of imaging Earth-size planets in the HZs of Sun-like stars. Roman is currently slated to launch as early as fall 2026, with science operations beginning in 2027.

In addition to Roman, at least two other exoplanet missions led by the European Space Agency are expected to launch within the next 1–4 years. The PLAnetary Transits and Oscillations of stars (PLATO) mission will continue the legacy of Kepler and TESS by observing bright stars in large areas of the sky to detect and characterize transiting planets down to $\sim 1 R_{\oplus}$ whose masses

²<https://www.stsci.edu/~nnikolov/TrExoLiSTS/JWST/trexolists.html>

can be determined by ground-based RV follow up (Rauer et al. 2014). PLATO’s high-precision photometry will also enable asteroseismology of planet host stars, yielding precise stellar mass, radius, and age measurements, and hence more accurate demographics of small planets orbiting in the HZs of Sun-like stars. Excitingly, PLATO should also be able to detect some moons and rings around exoplanets thanks to its high precision. Following PLATO, the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) mission will be launched as early as the late 2020s to investigate the atmospheres of > 500 gaseous and rocky exoplanets (Tinetti et al. 2016). Similar to the goals of JWST’s exoplanet investigations, ARIEL will probe the $0.5\text{--}7.8\text{ }\mu\text{m}$ spectra of primarily hot and warm planets orbiting close to their host stars in order to learn about their atmospheric physics, chemistry, and formation processes.

For ground-based observations, the 30-m-class extremely large telescopes (ELTs) will see first light within the next decade. The huge apertures of the ELTs will act as photon buckets, shortening integration times for faint objects while also improving the diffraction-limited angular resolution that can be achieved with AO systems. Planned instruments for the ELTs will leverage these advantages to learn more about planet formation and habitability in the solar neighborhood. For example, combining high-contrast imaging with high-dispersion spectroscopy could enable ELTs to search for biosignatures in the atmospheres of rocky planets around our nearest neighbor stars (Snellen et al. 2015). On the European ELT (E-ELT),³ the planned Mid-infrared ($3\text{--}13\text{ }\mu\text{m}$) ELT Imager and Spectrograph (METIS; Brandl et al. 2010) is expected to achieve $\sim 10^{-7}$ contrast at an angular separation of $7\lambda/D$ (where λ is the wavelength of observation and D is the telescope aperture diameter), enabling potential detections of H_2O , O_2 , and CO_2 on Proxima Centauri b via high-resolution spectroscopy (Quanz et al. 2015; Turbet et al. 2016). In the optical–NIR ($0.4\text{--}1.8\text{ }\mu\text{m}$), the ArmazoNes high Dispersion Échelle Spectrograph (ANDES) on the E-ELT will also be a powerful instrument for a variety of exoplanet science cases, with uses ranging from transmission spectroscopy of small transiting planets to probing the compositions of inner protoplanetary disks (e.g., Palle et al. 2025). A complimentary suite of instruments are also being developed for the Giant Magellan Telescope (GMT),⁴ including a near-infrared spectrograph (GMTNIRS; Jaffe et al. 2016) and the GMT-consortium large earth finder (G-CLEF; Szentgyorgyi et al. 2016), a visible échelle spectrograph that will allow precision RV measurements ($0.1\text{--}0.5\text{ m s}^{-1}$) and optical transmission spectroscopy of rocky planets in the HZ (e.g., Rodler and López-Morales 2014).

Finally, in the long term (2040s and beyond), high-contrast imaging and spectroscopy from space will allow direct measurements of potential biosignatures in the atmospheres of rocky HZ planets orbiting Sun-like stars. In the mid-IR, the Large Interferometer For Exoplanets (LIFE) mission will use nulling interferometry to measure the thermal emission of exoplanets and detect $\sim 25\text{--}45$ rocky exoplanets ($0.5\text{--}1.5\text{ R}_{\oplus}$) orbiting in the HZ of their host stars (Quanz et al. 2022b; Dannert et al. 2022; Hansen et al. 2022). LIFE will measure the $\sim 3\text{--}20\text{ }\mu\text{m}$ emission spectra of dozens of exoEarth candidates to identify potential biosignature molecules (e.g., CO_2 , H_2O , O_3 , and CH_4) and constrain the occurrence rate of Earth-like planets orbiting Sun-like stars (e.g., Konrad et al. 2022; Alei et al. 2022; Kammerer et al. 2022). Synergies between LIFE and

³<https://elt.eso.org>

⁴<https://giantmagellan.org>

HWO, which will characterize exoEarth candidates in the UV–NIR, will lead to more robust interpretations of possible biosignatures and lower the risk of false-positive exoEarth detections (e.g., Carrión-González et al. 2023; Alei et al. 2024).

Chapters 3–5 in this dissertation established some of the groundwork necessary for HWO, but additional precursor/preparatory work must be accomplished in the near-term to ensure that HWO has clear science goals and meets the technological requirements necessary to achieve them. NASA’s HWO Technology Maturation Project Office (HTMPO), in collaboration with the Community Science and Instrument Team (CSIT), is currently exploring potential observatory architectures and maturing the overall HWO mission concept (e.g., Vaughan et al. 2023; Stark et al. 2024a; Feinberg et al. 2026). As discussed in Chapters 4 and 5, thorough vetting of giant planets orbiting potential HWO targets is one critical precursor science avenue that the community can begin addressing today. Constraining the properties of companions in these systems is necessary for assessing HZ dynamical viability, an important input for science and engineering trade studies that reduce mission design risk by evaluating the impact of astrophysical realities and potential design choices (e.g., aperture size, starlight suppression requirements, astrometric precision) on the expected yield of potential exoEarths. Constraints on planetary system architectures also provide key astrophysical context for interpreting future observations of biosignatures (Batalha et al. 2019; Damiano et al. 2025), inferring planet formation pathways and evolutionary histories (Barnes and Raymond 2004; Tsiganis et al. 2005), and investigating the role of planetary siblings in shaping habitable environments via dynamical interactions and volatile delivery (Raymond et al. 2004, 2008).

In future work, I plan to assess the population of (sub)stellar companions in additional potential HWO target systems by combining both existing and new RV measurements (e.g., Chapter 5) together with time-series astrometric observations from Gaia DR4 (set to be released in late 2026). Including astrometry will improve mass estimates for RV-detected giant companions by constraining their orbital inclinations, and help to probe long-period parameter space via astrometric accelerations that long-baseline RVs are not yet sensitive to. I will start with the ExEP Mission Star List (Mamajek and Stapelfeldt 2024), then consider additional stars whose HZs would be accessible to HWO (e.g., Tuchow et al. 2024, 2025) to enable future science–engineering trade studies as some stars are de-prioritized or removed from the list (e.g., due to the presence of destabilizing giant planets in the HZ, prohibitively bright exozodi, or previously-unknown stellar companions). Then, using updated system parameters from new analyses of those observations, I will reassess the dynamical stability of hypothetical exoEarths in each system’s HZ (e.g., Kane et al. 2024; Kane and Burt 2024), leading to a set of new recommendations and future strategies for constraining the HWO target list. This future work will help determine the number of additional (and more distant) targets that HWO will need to observe to meet the exoEarth detection goals of the Astro2020 decadal, therefore driving key observatory design choices being considered by the CSIT and HTMPO such as the coronagraph inner working angle and telescope aperture size. This work will also help provide the astrophysical backdrop necessary for interpreting observations of potential living worlds that HWO and other future missions may one day discover.

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