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Giant Outer Transiting Exoplanet Mass (GOT ‘EM) Survey. II. Discovery of a Failed Hot Jupiter on a 2.7 Year, Highly Eccentric Orbit*

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ABSTRACT

Radial velocity (RV) surveys have discovered giant exoplanets on au-scale orbits with a broad distribution of eccentricities. Those with the most eccentric orbits are valuable laboratories for testing theories of high eccentricity migration. However, few such exoplanets transit their host stars thus removing the ability to apply constraints on formation from their bulk internal compositions. We report the discovery of Kepler-1704 b, a transiting 4.15 M_J giant planet on a 988.88 day orbit with the extreme eccentricity of $0.921^{+0.010}_{-0.015}$. Our decade-long RV baseline from the Keck I telescope allows us to measure the orbit and bulk heavy element composition of Kepler-1704 b and place limits on the existence of undiscovered companions. Kepler-1704 b is a failed hot Jupiter that was likely excited to high eccentricity by scattering events that possibly began during its gas accretion phase. Its final periastron distance was too large to allow for tidal circularization, so now it orbits its host from distances spanning 0.16–3.9 au. The maximum difference in planetary equilibrium temperature resulting from this elongated orbit is over 700 K. A simulation of the thermal phase curve of Kepler-1704 b during periastron passage demonstrates that it is a remarkable target for atmospheric characterization from the *James Webb Space Telescope*, which could potentially also measure the planet’s rotational period as the hot spot from periastron rotates in and out of view. Continued characterization of the Kepler-1704 system promises to refine theories explaining the formation of hot Jupiters and cool giant planets like those in the solar system.

1. INTRODUCTION

Giant planet migration is typically invoked to explain the present day architecture of exoplanetary systems. Theories of planetary migration abound but can broadly be categorized as disk-driven migration, caused by torques from the protoplanetary disk (e.g., Goldreich & Tremaine 1980; Lin & Papaloizou 1986; Ward 1997; Baruteau et al. 2014), or high-eccentricity migration (HEM), whereby a giant planet exchanges orbital energy and angular momentum with one or more other objects in its system and subsequently experiences tidal circularization during close periastron passages

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(e.g., Rasio & Ford 1996; Wu & Murray 2003; Nagasawa et al. 2008; Wu & Lithwick 2011). The characterization of giant planets and their orbits offers a window into which mechanisms might have been at play.

There are multiple pathways for generating high eccentricities including Kozai-Lidov oscillations (Kozai 1962; Lidov 1962) induced by a stellar companion (e.g., Wu & Murray 2003; Fabrycky & Tremaine 2007; Naoz et al. 2012) or planetary companion (e.g., Naoz et al. 2011; Lithwick & Naoz 2011), planet-planet scattering (e.g., Rasio & Ford 1996; Ford & Rasio 2006; Chatterjee et al. 2008; Jurić & Tremaine 2008; Raymond et al. 2010; Nagasawa & Ida 2011), and secular chaos (e.g., Wu & Lithwick 2011; Hamers et al. 2017). Each mechanism can excite the eccentricity of a giant planet and, in doing so, imprints identifying (although not necessarily unique) clues in the present day system. Disentangling all the possible migration pathways for a single system or even determining the fraction of systems that migrated through various channels is challenging, though (e.g., Fabrycky & Winn 2009; Socrates et al. 2012; Dawson et al. 2015; Dawson & Murray-Clay 2013).

HEM theories are readily tested in systems containing hot Jupiters, giant planets on orbits shorter than ~ 10 days that are thought to have formed at greater distances from their host stars (for a recent review, see Dawson & Johnson 2018). In addressing the mysteries of giant planet HEM, it is beneficial not only to investigate hot giant planets themselves but also *proto-* and *failed* hot Jupiters, objects in the process of becoming hot Jupiters or those that followed a similar evolutionary pathway but will not become hot Jupiters, respectively. HD 80606 b (e.g., Naef et al. 2001; Moutou et al. 2009; Winn et al. 2009) is possibly a proto-hot Jupiter caught in the act of tidal circularization (e.g., Wu & Murray 2003; Fabrycky & Tremaine 2007; Socrates et al. 2012). Motivated by this planet, Socrates et al. (2012) theorized that if HEM is the preferred pathway of hot Jupiter migration, then the *Kepler* mission (Borucki et al. 2010) should detect a population of highly eccentric ($e > 0.9$) giant planets and their current orbital periods (P) should distinguish which are likely to be proto-hot Jupiters ($P \lesssim 2$ years) or failed hot Jupiters ($P \gtrsim 2$ years). This theory was supported by the detection of highly eccentric eclipsing binaries by *Kepler* (Dong et al. 2013). However, similar support was not offered by *Kepler*'s planet discoveries. Based on analyses of the photoeccentric effect (Ford et al. 2008; Dawson & Johnson 2012), Dawson et al. (2015) reported a paucity of proto-hot Jupiters on highly eccentric orbits in the *Kepler* sample even after considering the limited sensitivity of transit surveys to planets with orbital distances of a few au. This work instead suggested that the dominant pathway of hot Jupiter formation is either disk migration or interaction with a planetary rather than stellar companion causing HEM to begin interior to 1 au.

Only one proto-hot Jupiter candidate was identified, Kepler-419 b (Dawson et al. 2012), which was later labeled as a failed hot Jupiter after subsequent (RV) observations (Dawson et al. 2014).

Although RV surveys have detected a handful of failed hot Jupiter exoplanets, Kepler-419 b stands alone owing to its transiting geometry. By definition, a failed hot Jupiter must have a sufficiently wide orbit such that its periastron distance (despite its high eccentricity) is too large for tidal forces to efficiently circularize its orbit. By the observational biases of the transit method (e.g., Beatty & Gaudi 2008), such long-period planets are unlikely to be observed in transit (e.g., Dalba et al. 2019), although eccentricity can increase this probability (e.g., Kane 2007). According to the NASA Exoplanet Archive¹, of the 16 non-controversial exoplanets with measured eccentricity above 0.8, only Kepler-419 b, HD 80606 b, and Kepler-1656 b (Brady et al. 2018) have measured radii. Increasing this threshold to $e > 0.9$ leaves only HD 80606 b.

Those rare few eccentric, long-period giant exoplanets that do transit their hosts are exceptionally valuable because their radii and bulk compositions provide new windows into their formation and migration. Metal-rich stars preferentially host eccentric hot Jupiters (Dawson & Murray-Clay 2013; Buchhave et al. 2018), lending credence to theories of planet-planet scattering since host star metallicity is known to correlate with giant planet occurrence (e.g., Gonzalez 1997; Santos et al. 2004; Fischer & Valenti 2005). Furthermore, empirical trends in giant planet metal enrichment (relative to stellar) with planet mass hint at a fundamental and expected connection between the metal content of stars and their planets (Miller & Fortney 2011; Thorngren et al. 2016; Teske et al. 2019). With this in mind, giant planet bulk metallicity is likely a key piece of information for understanding migration history (e.g., Alibert et al. 2005; Ginzburg & Chiang 2020; Shibata et al. 2020).

As the second discovery of the Giant Outer Transiting Exoplanet Mass (GOT 'EM) survey (Dalba et al. 2021a), we present a new failed hot Jupiter from the *Kepler* sample: KOI-375.01 (hereafter Kepler-1704 b as we will confirm its planetary nature). In Section 2, we show the observations of this system including photometry from the *Kepler* spacecraft that detected two transits spaced by 989 days, follow-up adaptive optics (AO) imaging, and a follow-up Doppler spectroscopy spanning a decade. In Section 3, we combine these data sets through the comprehensive modeling of system parameters using EXOFASTv2 (Eastman et al. 2013, 2019). In Section 4, we conduct a thorough analysis to explore the plausibility of planetary or stellar companions across a

¹ Accessed 2021 February 2 (<https://exoplanetarchive.ipac.caltech.edu/>).

wide swath of orbital separation space. We also retrieve this planet’s bulk metallicity and simulate its reflected light phase curve, the detection of which would be an unprecedented discovery that is within the anticipated capability of the *James Webb Space Telescope* (*JWST*). In Section 5, we offer our interpretation of all of the analyses of the Kepler-1704 system in regards to the formation history of Kepler-1704 b and motivate a campaign to measure the stellar obliquity during a future transit. In Section 6, we summarize our findings.

2. OBSERVATIONS

We employ photometric, spectroscopic, and imaging observations in our analysis of the Kepler-1704 system. In the following sections, we describe how each of these data sets was collected and processed.

2.1. Photometric Data from Kepler

The *Kepler* spacecraft observed Kepler-1704 at 30-minute cadence in all 18 quarters of its primary mission. We accessed the Pre-search Data Conditioning Simple Aperture Photometry (PDCSAP; Jenkins et al. 2010; Smith et al. 2012; Stumpe et al. 2012) through the Mikulski Archive for Space Telescopes (MAST), stitching together the light curves from individual quarters into one time series with a common baseline flux using *lightkurve* (Lightkurve Collaboration et al. 2018). We further cleaned the photometry by removing all data points flagged for “bad quality” and dividing out the median background flux to produce a normalized light curve. We then measured a preliminary time of conjunction, duration, and period for the transiting planet using a box least squares transit search (BLS; Kovács et al. 2002), identifying only two transit events in Quarters 2 and 13. The time separating these two transits was 989 days, the suspected orbital period of Kepler-1704 b. However, the data gap between Quarters 7 and 8 occurred precisely in between these transits, introducing a ~ 494 -day orbital period alias.

We used the BLS results to mask out both transits and detrend any variability in the light curve without risk of obscuring the signal. Interpolating over the masked transit events, we fit a smoothed curve to systematics in the photometry using a Savitzky–Golay filter (Virtanen et al. 2020) and then subtracted out this additional structure to produce our final data product. Before unmasking the transit events, we clipped any remaining individual outliers with residuals to the smoothed fit that were greater than $3\text{-}\sigma$ discrepant.

We present the binned, detrended *Kepler* transits of Kepler-1704 b in Figure 1. Under the assumption of a circular edge-on orbit, the mean transit duration of Kepler-1704 b and stellar properties reported by the NASA Exoplanet Archive suggest an orbital period of approximately 11 days. This scenario is thoroughly ruled out by the extensive *Kepler* data set. Instead, we explored the possibility that orbital eccentricity affected the duration of the transit.

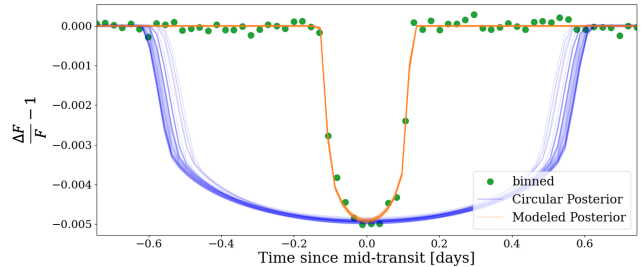


Figure 1. Phase-folded, binned *Kepler* data for Kepler-1704 b (green dots). The transit duration is substantially shorter than expected for a circular orbit assuming the stellar density listed in Table 2 even when fit for impact parameter (blue models). The data are better reproduced by models with high eccentricity (orange lines).

2.1.1. Photoeccentric Transit Modeling

The observed transits of Kepler-1704 b have a duration of ~ 6 hours, which is nearly 5 times shorter than would be expected for a Jovian-size planet with a 989 day orbital period. The two plausible sources of this discrepancy are high impact parameter (b) or high eccentricity (e), but a preliminary transit fit reveals that high b alone cannot account for the anomalously short transit duration. We instead developed a model to account for both of these properties through a photometric transit fit that takes into consideration the *photoeccentric* framework of Dawson & Johnson (2012), as shown in Figure 1.

We modeled the standard transit parameters, including orbital period (P), time of conjunction (T_C), planet-star radius ratio (R_p/R_*), and b , along with the expected stellar density assuming a circular orbit, $\rho_{*,\text{circ}}$, to obtain a model that encodes information about the true orbital eccentricity of the planet according to Kipping et al. (2012b). We derived this dynamical information from our results by comparing our modeled $\rho_{*,\text{circ}}$ to the true stellar density, ρ_* , represented by the median of our EXOFASTv2 ρ_* posterior (Section 3). A value of $\rho_{*,\text{circ}}$ greater than ρ_* would imply that the planet transited faster than expected and vice versa, given an initial assumption of $e = 0$. Breaking from this assumption, however, we calculated which values of e and the argument of periastron (ω) were necessary to account for the unusually fast transit, subsequently bringing $\rho_{*,\text{circ}}$ into agreement with ρ_* . For both parameters, we calculated posterior probability distributions using the log-likelihood function (Dawson & Johnson 2012)

$$\log P(e, \omega | \rho_*, \rho_{*,\text{circ}}) = -\frac{1}{2} \left(\frac{g(e, \omega)^3 \rho_* - \rho_{*,\text{circ}}}{g(e, \omega)^3 \sigma_{\rho_*}} \right)^2 \quad (1)$$

where

$$g(e, \omega) = \frac{1 + e \sin \omega}{\sqrt{1 - e^2}}, \quad (2)$$

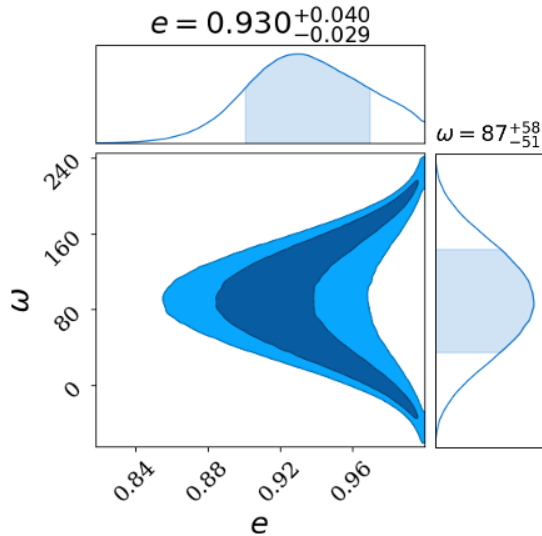


Figure 2. Posterior probabilities distributions for orbital eccentricity (e) and argument of periastron (ω , in degrees) from the photoeccentric modeling. The shaded regions in the 1D histograms are 68% credible intervals, and the shaded contours in the 2D histogram are the 68% and 95% credible regions. Values reported are the median and 68% credible intervals.

following the notation of [Kipping \(2010\)](#) and [Kipping et al. \(2012b\)](#).

Constraints on ω using this method tend to be broad, but they are sufficient to determine if a transit occurs closer to periastron (as is the case for Kepler-1704 b) or apastron. On the other hand, we were able to constrain the eccentricity of Kepler-1704 b here with high certainty. We found that the 68% credible interval for eccentricity is 0.901–0.970 (Figure 2).

In a previous analysis of the photoeccentric effect in *Kepler* transit data, [Dawson et al. \(2015\)](#) found 0_{-0}^{+1} giant planets on highly eccentric orbits that are likely undergoing tidal circularization. This non-detection refuted the hypothesis of [Socrates et al. \(2012\)](#) that approximately four such planets should be detected if HEM is the dominant hot Jupiter migration mechanism. [Dawson et al. \(2015\)](#) only considered planet candidates with three or more transits, to more accurately account for the completeness of *Kepler* pipeline detections (e.g., [Christiansen et al. 2020](#)), so Kepler-1704 was not included in their analysis.

Assuming tidal decay at constant angular momentum, the highest allowed values of eccentricity from our photoeccentric modeling would produce a final orbital period below 10 days, the canonical threshold for hot Jupiters. Therefore, based on just this photoeccentric effect analysis, Kepler-1704 b is a candidate proto-hot Jupiter. However, additional orbital characterization via RV monitoring of the host is needed to refine the eccentricity and the nature of Kepler-1704 b.

2.2. Spectroscopic Data from HIRES

We acquired 15 high resolution spectra of Kepler-1704 with the High Resolution Echelle Spectrometer (HIRES; [Vogt et al. 1994](#)) on the Keck I telescope in support of our Doppler monitoring of the Kepler-1704 system. The baseline of these observations spans nearly a decade. For each observation, the starlight passed through a heated iodine cell before reaching the slit to enable the precise wavelength calibration of each RV measurement.

We did not acquire a high signal-to-noise (S/N) template spectrum as is typical for HIRES RV observations (e.g., [Howard et al. 2010](#)). Instead, we identified a pre-existing, “best match” template spectrum in the HIRES spectral library following [Dalba et al. \(2020a\)](#). The best match star was HD 203473, a brighter G6V star with similar spectroscopic properties to Kepler-1704 according to a [SpecMatch–Emp²](#) analysis ([Yee et al. 2017](#)). The use of a best match template incurs extra uncertainty in addition to internal RV errors. Following conservative estimations by [Dalba et al. \(2020a, their Table 2\)](#), we added 6.2 m s^{-1} to our internal RV errors in quadrature to account for this method. After swapping in the template of HD 203473, the RV extraction proceeded following the standard forwarding techniques employed by California Planet Search (e.g., [Howard et al. 2010](#); [Howard & Fulton 2016](#)).

We provide the full RV data set for Kepler-1704 in Table 1. The uncertainties listed include the additional uncertainty incurred by the matched-template method of RV extraction ([Dalba et al. 2020a](#)). We also include corresponding S_{HK} activity indicators derived from the Ca II H and K spectral lines ([Wright et al. 2004](#); [Isaacson & Fischer 2010](#)).

We note that the first RV measurement (from BJD = 2455669) is the least precise observation in the series. Its uncertainty is three standard deviations above the mean. This larger error is not surprising as the exposure time for the spectrum used to measure that RV was substantially shorter than the others. The resulting best fit velocity in each two-angstrom chunk of spectrum, which typically only contain one stellar and one iodine line, was less precise, leading to the larger error in RV. When folded on the ephemeris of Kepler-1704 b, this data point occupies a non-critical phase in the orbit. However, this data point extends the baseline of RVs observations by 826 days and is critical to our consideration of acceleration in the Kepler-1704 system (Section 4.2). Although there is no obvious reason to exclude this data point from our analysis besides its larger uncertainty, we will treat this data point with skepticism moving forward.

In Section 3, we model the RVs and transits simultaneously, confirming that the orbital period of Kepler-1704 b is

² <https://github.com/samuelyeewl/specmatch-emp>

Table 1. RV Measurements of Kepler-1704

BJD _{TDB}	RV (m s ⁻¹)	S _{HK}
2455669.111196	25.3±8.5	0.0966±0.0010
2456495.013178	28.9±6.8	0.1220±0.0010
2456532.811313	31.3±6.8	0.1330±0.0010
2458383.894210	16.2±7.5	0.1609±0.0010
2458593.029972	38.6±6.8	0.1172±0.0010
2458679.811045	63.2±6.8	0.1260±0.0010
2458765.877254	68.1±6.8	0.1311±0.0010
2458815.758493	90.0±7.2	0.1267±0.0010
2459006.997818	195.5±6.8	0.1222±0.0010
2459038.992753	-118.9±6.9	0.1222±0.0010
2459041.035816	-119.9±7.1	0.1205±0.0010
2459051.874260	-93.1±6.7	0.1265±0.0010
2459070.992339	-72.1±7.2	0.0964±0.0010
2459189.758826	-31.5±7.6	0.1183±0.0010

accurately represented by the time elapsed between the two *Kepler* transits (988.88 days) and not half of that value. Visual inspection of the RV data folded on an orbital period of 494.44 days suggests no Keplerian signal at this periodicity. Therefore, we hereafter do not consider the possibility that another transit occurred during the gap in observations between *Kepler* quarters 7 and 8.

2.3. Archival AO Imaging

The Kepler-1704 system has been observed in several imaging campaigns previously (for a summary, see Furlan et al. 2017). To explore the existence of bound or background stellar neighbors, we present three data sets acquired from the Exoplanet Follow-up Observing Program³.

The first imaging data set comprises AO images from the PHARO instrument (Hayward et al. 2001) at the 200 inch telescope at Palomar Observatory as published by Wang et al. (2015a). This work used a 3-point dither pattern to obtain a set of images in the K_s band that were combined and searched for stellar companions (Figure 3, left panel). Wang et al. (2015a) claimed two detections: one source with $\Delta K_s = 3.3$ with a separation and position angle (PA) of 5''47 and 157.0°, respectively, and another source with $\Delta K_s = 4.6$ with a separation and PA of 3''19 and 305.5°, respectively. Both detections are visible in the left panel of Figure 3. The source with PA=157.0° (indicated by a green, vertical arrow) is resolved by Gaia (Gaia Collaboration et al. 2016, 2020) and has the EDR3 source ID of 2136191732305041920 (hereafter *Gaia-213* for simplicity). The parallax and proper motion

of Kepler-1704 and *Gaia-213* as measured by Gaia definitively show that these two stars are not gravitationally associated. The other source identified by Wang et al. (2015a), as well as a brighter source near the upper edge of the image that was not identified by Wang et al. (2015a), are not present in the Gaia EDR3 catalog. In the left panel of Figure 3, these unidentified sources are shown with horizontal yellow arrows.

The second imaging data set also comprises AO images from the PHARO instrument but in the Br- γ filter as published by Furlan et al. (2017). Surprisingly, only Kepler-1704 and *Gaia-213* (at PA=157.0°) are visible despite deeper magnitude limits near 3''19: $\Delta K_s = 4.9$ versus $\Delta \text{Br-}\gamma = 7.0$ (Wang et al. 2015a; Furlan et al. 2017). The time elapsed between the epochs of imaging, roughly one month, is too short to explain the discrepancy.

The solution to this conundrum lies in the relative positioning of the two sources in question with respect to the positioning of Kepler-1704 and *Gaia-213*. The separation and PA between these two pairs are identical. Visual inspection suggests that the contrast between the stars in each pair is also similar. Thus, our conclusion is that the two sources identified by yellow, horizontal arrows in the left panel Figure 3 are spurious duplications of Kepler-1704 and *Gaia-213* caused by an accidental image alignment error.

The third imaging data set comprises AO images from the NIRC2 instrument (Wizinowich et al. 2000) at the Keck II telescope as published by Furlan et al. (2017). Observations were taken in the Br- γ filter and the field of view was too small to include any of the other sources (astrophysical or spurious) mentioned previously (Figure 4). The NIRC2 data yield a nondetection of a stellar neighbor within 2'' with delta-magnitude limits of 8.4 and 8.7 at separations of 0''5 and 1''0, respectively (Furlan et al. 2017). Since the NIRC2 observations of Kepler-1704 provide the strongest constraints on neighboring stars, we continue our analysis using only these data.

We used the NIRC2 contrast curve (i.e., 5σ limiting delta-magnitude as a function of separation) to derive the corresponding limiting mass for a bound companion. First, we downloaded a MESA Isochrones and Stellar Tracks (MIST) isochrone (Paxton et al. 2011, 2013, 2015; Dotter 2016; Choi et al. 2016) from the MIST web interpolator⁴. We provided values of initial stellar metallicity, extinction, and age based on the system modeling described in Section 3. This isochrone provide a numerical relationship between stellar mass and absolute K_s magnitude, which we treated interchangeably with Br- γ . After converting absolute magnitude to apparent magnitude (using the distance from Sec-

³ ExoFOP, accessed 2021 February 5 (<https://exofop.ipac.caltech.edu/>).

⁴ Accessed 2020 December 17 (<http://waps.cfa.harvard.edu/MIST/>).

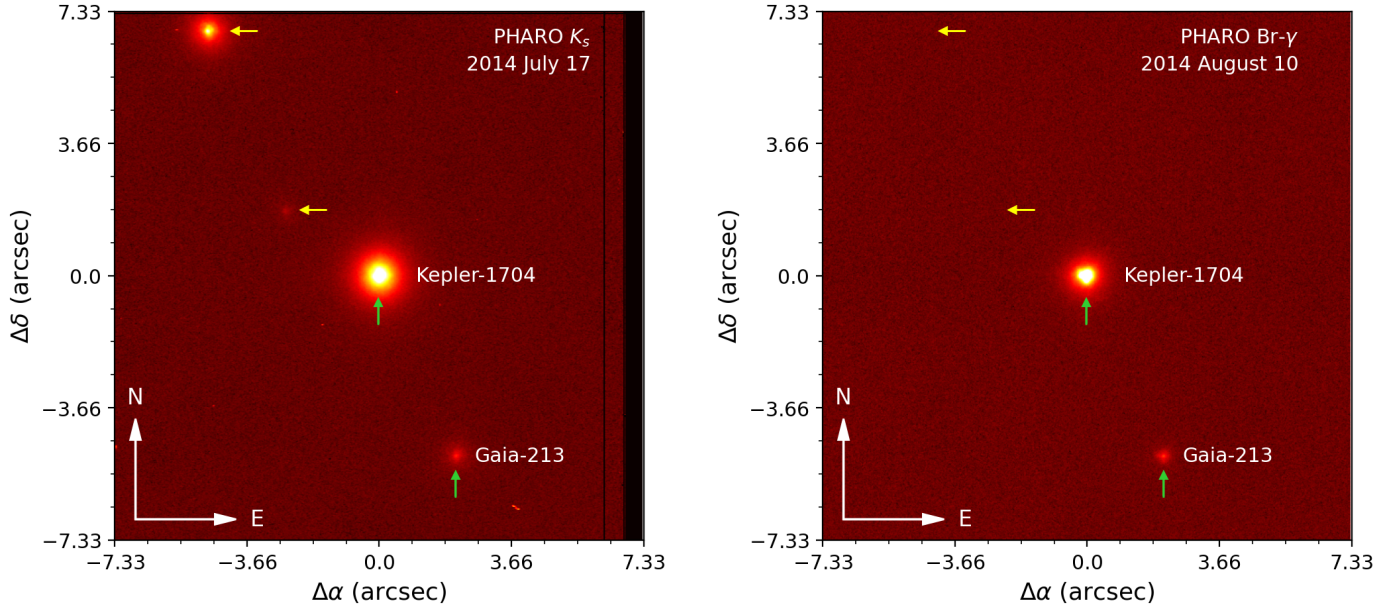


Figure 3. AO images of Kepler-1704 taken with the PHARO instrument on the 200 inch telescope at Palomar Observatory and acquired from ExoFOP. *Left:* Observation from Wang et al. (2015a) showing Kepler-1704 and three other sources. Green, vertical arrows identify Kepler-1704 (at center) and *Gaia-213* (see text), as resolved by Gaia. Yellow, horizontal arrows identify two additional sources not resolved by Gaia, the fainter of which was claimed as a detection by Wang et al. (2015a). The white stripes on the eastern edge of the image are mosaicking artifacts. *Right:* PHARO observation from Furlan et al. (2017) showing Kepler-1704 at center and *Gaia-213*. In both images, the scales and locations of the arrows are identical. The two sources present in the left panel that are absent in the right panel are spurious duplications of Kepler-1704 and *Gaia-213* caused by an alignment error. According to Gaia astrometry, *Gaia-213* is not gravitationally bound to Kepler-1704.

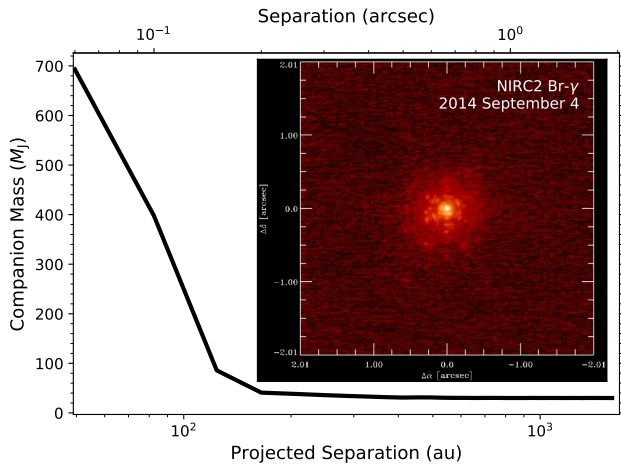


Figure 4. Upper limit on companion mass in the Kepler-1704 system based on the contrast curve measured from NIRC2 AO images. The masses were estimated by interpolating a MIST isochrone (in the stellar regime) and a brown dwarf isochrone (in the substellar regime). The inset is the NIRC2 image of Kepler-1704 published by Furlan et al. (2017).

tion 3), we interpolated the ΔK_s values with those measured by NIRC2 to calculate an upper limit of companion mass as a function of projected separation (Figure 4). At wider separations, the delta-magnitude values exceeded those in the MIST

isochrone. For those separations we instead interpolated a 5 Gyr brown dwarf isochrone from Baraffe et al. (2003). Beyond a projected separation of ~ 200 au, we find that any companion in the Kepler-1704 system must have a mass below $\sim 32 M_J$.

3. MODELING THE STELLAR AND PLANETARY PARAMETERS

We simultaneously fit models to the transit and RV data for Kepler-1704 while also modeling the stellar spectral energy distribution (SED) using the EXOFASTv2 suite. The result was a set of precise, consistent stellar (Table 2) and planetary (Table 3) parameters.

We began by defining informative priors on several stellar parameters, which are listed at the top of Table 2. We constrained stellar effective temperature (T_{eff}) and metallicity (as described by $[\text{Fe}/\text{H}]$) based on a SpecMatch⁵ analysis (Petigura 2015; Petigura et al. 2017) of a moderate S/N (~ 40) spectrum of Kepler-1704 acquired with Keck-HIRES without the iodine cell. This analysis produced an uncertainty on T_{eff} of 100 K, which we inflated to 115 K, in line with the systematic uncertainty floor reported by Tayar et al. (2020). The SpecMatch analysis also suggested that the stellar ra-

⁵ <https://github.com/petigura/specmatch-syn>

Table 2. Median values and 68% confidence intervals for the stellar parameters for Kepler-1704.

Parameter	Units	Values
Informative Priors:		
T_{eff}	Effective Temperature (K) . . .	$\mathcal{N}(5772, 115)$
[Fe/H]	Metallicity (dex)	$\mathcal{N}(0.2, 0.06)$
ϖ	Parallax (mas)	$\mathcal{N}(1.213, 0.016)$
A_V	V-band extinction (mag)	$\mathcal{U}(0, 0.2902)$
Stellar Parameters:		
M_*	Mass (M_\odot)	$1.131^{+0.040}_{-0.051}$
R_*	Radius (R_\odot)	$1.697^{+0.058}_{-0.059}$
L_*	Luminosity (L_\odot)	$2.83^{+0.17}_{-0.19}$
F_{Bol}	Bolometric Flux (cgs)	$1.333 \times 10^{-10+7.3 \times 10^{-12}}_{-8.5 \times 10^{-12}}$
ρ_*	Density (g cm^{-3})	$0.325^{+0.036}_{-0.032}$
$\log g$	Surface gravity (cgs)	4.031 ± 0.032
T_{eff}	Effective Temperature (K)	5745^{+88}_{-89}
[Fe/H]	Metallicity (dex)	0.196 ± 0.057
[Fe/H] ₀	Initial Metallicity ^a	$0.218^{+0.054}_{-0.055}$
Age	Age (Gyr)	$7.4^{+1.5}_{-1.0}$
EEP	Equal Evolutionary Phase ^b	$453.0^{+4.5}_{-5.8}$
A_V	V-band extinction (mag)	$0.187^{+0.068}_{-0.091}$
σ_{SED}	SED photometry error scaling	$1.05^{+0.42}_{-0.26}$
ϖ	Parallax (mas)	1.213 ± 0.016
d	Distance (pc)	825 ± 11

See Table 3 in Eastman et al. (2019) for a detailed description of all parameters and all default (non-informative) priors beyond those specified here. $\mathcal{N}(a, b)$ denotes a normal distribution with mean a and variance b^2 . $\mathcal{U}(a, b)$ denotes a uniform distribution over the interval $[a, b]$.

^a Initial metallicity is that of the star when it formed.

^b Corresponds to static points in a star's evolutionary history. See Section 2 of Dotter (2016).

dius is $\sim 1.7 R_\odot$, hinting that this G2 star has evolved off of the main sequence (see Section 3.1). In addition to T_{eff} and [Fe/H], we constrained the upper limit on V-band extinction using the galactic reddening maps of Schlafly & Finkbeiner (2011). Lastly, we constrained the parallax of Kepler-1704 as measured by Gaia in EDR3 (Gaia Collaboration et al. 2016, 2020). Following the astrometric solution of Lindgren et al. (2020)⁶, we subtracted -0.026 ± 0.013 mas from the EDR3 value.

For the SED portion of the EXOFASTv2 fit, we modeled broadband photometry from 2MASS (Cutri et al. 2003), ALLWISE (Cutri et al. 2014), and Gaia (Gaia Collaboration et al. 2018) with inflated uncertainties as recommended by Eastman et al. (2019). In doing so, we employed the MIST stellar evolution models (Paxton et al. 2011, 2013, 2015; Dotter 2016; Choi et al. 2016) packaged within EXOFASTv2.

⁶ We calculated the astrometric solution using the software described at <https://www.cosmos.esa.int/web/gaia/edr3-code>.

Table 3. Median values and 68% confidence interval of the planet parameters for Kepler-1704 b.

Parameter	Units	Values
P	Period (days)	$988.88113^{+0.00091}_{-0.00092}$
R_p	Radius (R_J)	$1.065^{+0.043}_{-0.041}$
M_p	Mass ^a (M_J)	4.15 ± 0.29
T_C	Time of conjunction (BJD _{TDB})	$2455071.68459^{+0.00062}_{-0.00064}$
a	Semi-major axis (au)	$2.026^{+0.024}_{-0.031}$
i	Inclination (degrees)	$89.01^{+0.59}_{-0.27}$
e	Eccentricity	$0.921^{+0.010}_{-0.015}$
ω	Argument of Periastron ^b (degrees)	$83.0^{+4.5}_{-4.9}$
T_{eq}	Equilibrium temperature ^c (K)	$253.8^{+3.7}_{-4.1}$
τ_{circ}	Tidal circularization timescale ^d (Gyr)	$80000^{+150000}_{-46000}$
K	RV semi-amplitude (m s^{-1})	190^{+17}_{-16}
$\dot{\gamma}$	RV slope ^e ($\text{m s}^{-1} \text{ day}^{-1}$)	$0.0031^{+0.0029}_{-0.0027}$
R_p/R_*	Radius of planet in stellar radii	$0.0644^{+0.0016}_{-0.0011}$
a/R_*	Semi-major axis in stellar radii	$256.4^{+9.3}_{-8.6}$
τ	Ingress/egress transit duration (days)	$0.0172^{+0.0039}_{-0.0022}$
T_{14}	Total transit duration (days)	$0.2502^{+0.0034}_{-0.0026}$
T_{FWHM}	FWHM transit duration (days)	0.2326 ± 0.0017
b	Transit Impact parameter	$0.36^{+0.16}_{-0.24}$
b_S	Eclipse impact parameter	$7.6^{+2.4}_{-4.8}$
ρ_p	Density (g cm^{-3})	$4.06^{+0.54}_{-0.48}$
$\log g_p$	Surface gravity (cgs)	$3.937^{+0.039}_{-0.040}$
$\langle F \rangle$	Incident Flux ($10^9 \text{ erg s}^{-1} \text{ cm}^{-2}$)	$0.000465^{+0.000027}_{-0.000029}$
T_p	Time of Periastron (BJD _{TDB})	$2455071.37^{+0.20}_{-0.19}$
T_S	Time of eclipse (BJD _{TDB})	2454750 ± 110
Wavelength Parameters:		<i>Kepler</i>
u_1	linear limb-darkening coefficient	0.454 ± 0.039
u_2	quadratic limb-darkening coefficient	0.264 ± 0.049
Telescope Parameters:		<i>Keck-HIRES</i>
γ_{rel}	Relative RV Offset ^e (m/s)	$33.9^{+3.4}_{-3.6}$
σ_J	RV Jitter (m s^{-1})	$6.7^{+4.4}_{-4.2}$

See Table 3 in Eastman et al. (2019) for a detailed description of all parameters and all default (non-informative) priors. The coordinates of the planet are barycentric.

^a The value and uncertainty for M_p were determined using the full posterior distribution.

^b ω is the argument of periastron of the star's orbit due to the planet.

^c Calculated with Equation 3, which assumes no albedo and perfect redistribution. Between apastron and periastron, T_{eq} varies from 180–900 K. See the text for a discussion.

^d The tidal circularization timescales is calculated from Equation 4.

^e The reference epoch is $\text{BJD}_{\text{TDB}} = 2457429.435011$.

We imposed a noise floor of 2% on the bolometric flux used in the SED modeling following Tayar et al. (2020).

The EXOFASTv2 fit progressed until the number of independent draws of the underlying posterior probability distribution of each parameter exceeded 1000 and the Gelman–Rubin statistic for each parameter decreased below 1.01 (Gelman & Rubin 1992; Ford 2006). We show the result–

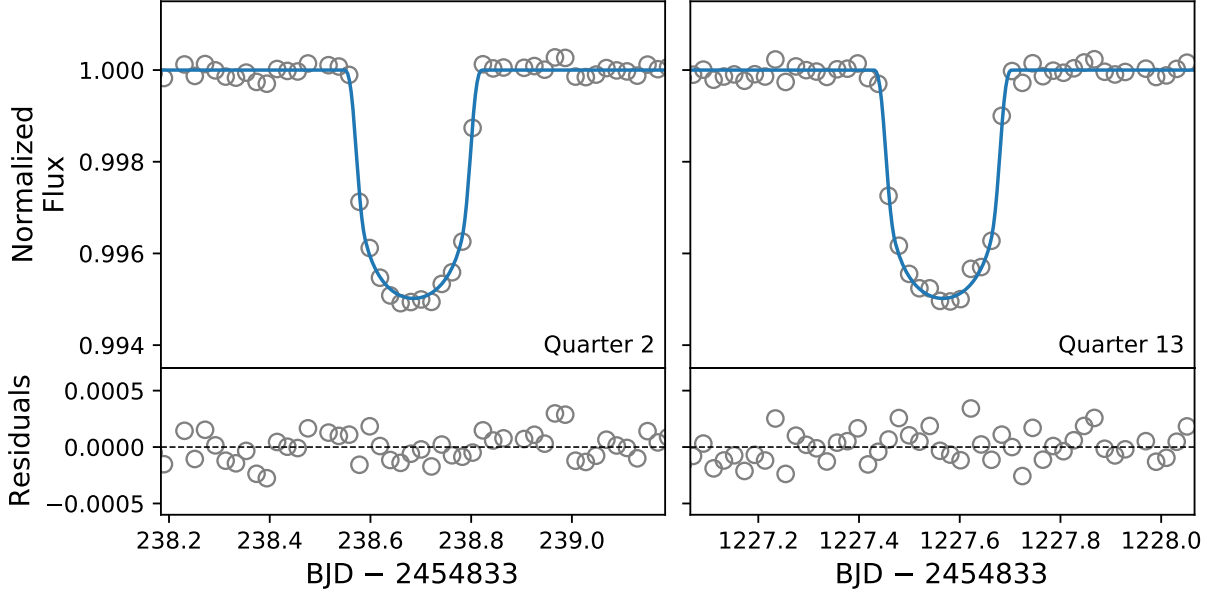


Figure 5. Detrended *Kepler* photometry of both transits (gray circles) and the best fit EXOFASTv2 model (blue line).

ing best fit models with the transit and RV data in Figures 5 and 6, respectively.

3.1. The Bimodality of Stellar Mass and Age

The converged EXOFASTv2 fit yielded bimodal posterior probability distributions for the stellar mass (M_*) and age (Figure 7). The region of parameter space preferred by the MIST stellar evolution models, as influenced by all of the *Kepler*-1704 data, exists near the subgiant branch as we suspected based on the *SpecMatch* radius estimation. EXOFASTv2 found that multiple stellar ages and surface gravity values ($\log g$) correspond to the T_{eff} prior, meaning that the bimodality is astrophysical and not due to inadequate posterior sampling. The bimodality propagates to the semi-major axis (a) of *Kepler*-1704 b and, to a lesser extent, its mass (M_p ; Figure 7).

Since we could not distinguish between the two families of solutions with the data of the *Kepler*-1704 system in hand, we adopted the strategy of *Ikwut-Ukwa et al. (2020)* and divided the solutions at a fiducial M_* value of $1.21 M_\odot$, which corresponds to the trough between the posterior probability peaks in Figure 7. The lower stellar mass, older age solution contains 51.8% of the posterior samples, which we treated as a slight preference over the higher stellar mass, younger solution. Therefore, in Tables 2 and 3, we only publish the parameters for the preferred, lower stellar mass solution. The only exception is the planet mass, M_p , for which we determine the 68% confidence interval using the full posterior distribution. None of our interpretations of the nature or formation history of *Kepler*-1704 b are changed by considering the alternate solution.

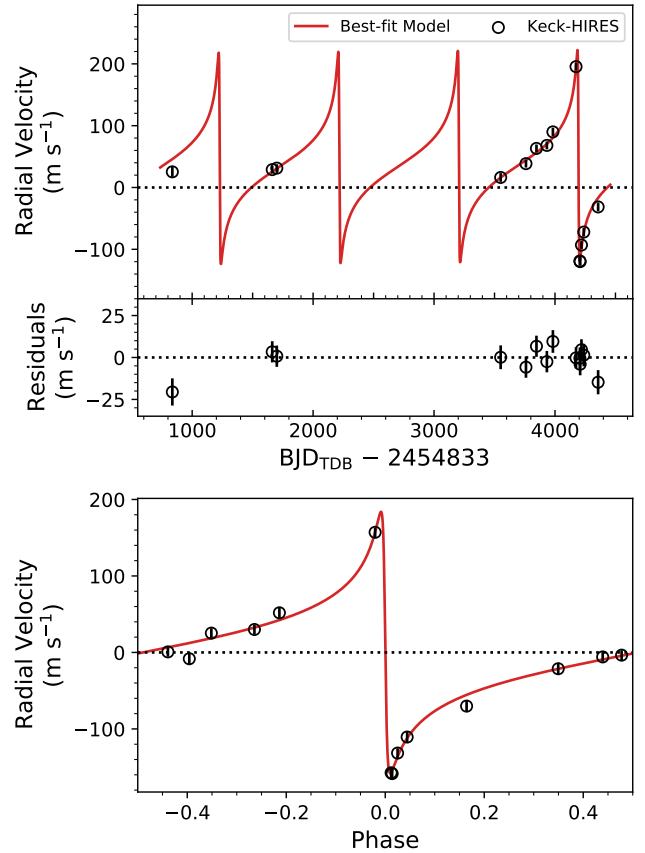


Figure 6. RV measurements of *Kepler*-1704 from Keck-HIRES with the best fit EXOFASTv2 model. The top panel shows the time series and the bottom panel shows the data phase-folded on the best-fit ephemeris with $P = 988.88$ days.

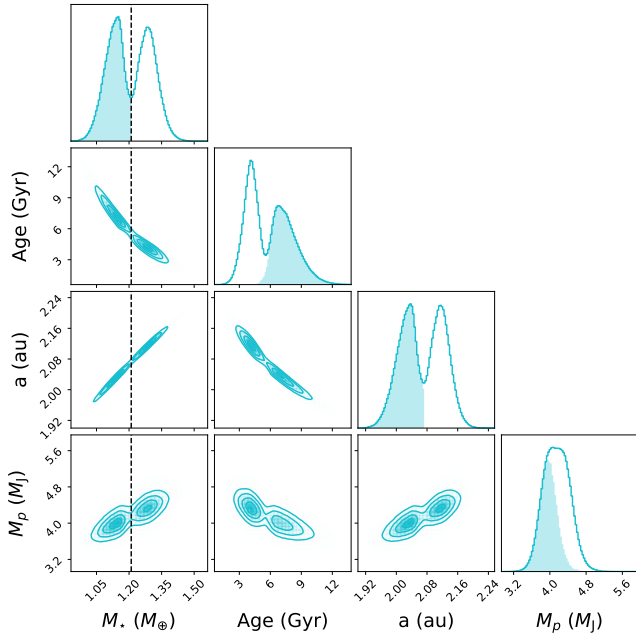


Figure 7. Posterior probability distributions showing the bimodality in stellar properties and its effect on the inferred properties of Kepler-1704 b. The dashed vertical line at $1.21 M_{\odot}$ shows where we separated the low and high mass solutions, the former of which is slightly preferred (51.8% to 48.2%) and is shown as the shaded portion of each distribution.

4. RESULTS

4.1. Confirming Kepler-1704 b as a Genuine Planet

A photometric dimming event with a depth corresponding to a giant planet transit can be created by substellar or stellar objects or various systematic signals (e.g., Brown 2003; Torres et al. 2005; Cameron 2012; Foreman-Mackey et al. 2016; Dalba et al. 2020a). False-positive signals can be harder to identify for longer (compared to shorter) orbital periods owing to the difficulty in quantifying the reliability of genuine transit events from similarly long-period exoplanets (e.g., Thompson et al. 2018). Indeed, Santerne et al. (2016) measured a 55% false-positive rate for *Kepler* giant planets within 400 days of orbital period. For these reasons, long-period giant planet candidates like KOI-375.01 must be vetted with Doppler spectroscopy before any weight is placed upon their standing as a genuine planet.

Our 10-year baseline of RV measurements for Kepler-1704 confirmed the genuine planetary nature of Kepler-1704 b. It also confirmed the 988.88 day orbital period, placing Kepler-1704 b among the top five longest-period (non-controversial) transiting exoplanets with precisely measured periods known to date⁷. With a semi-major axis of 2.03 au and an orbital ec-

⁷ According to the NASA Exoplanet Archive, accessed 2021 June 23.

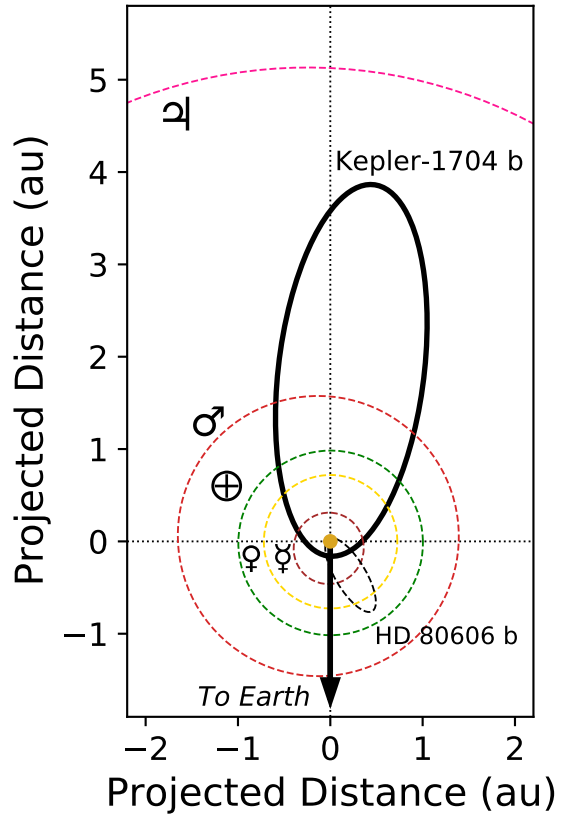


Figure 8. Face-on view of the orbit of Kepler-1704 b. The orbits of five Solar System planets and HD 80606 b (dashed black line) are included for reference. All orbits are drawn to scale, although the size of Kepler-1704 is not.

centricity of 0.92, its elongated orbit brings it within 0.16 au of its host star and then slingshots it out to 3.9 au—the largest apastron distance of any transiting exoplanet with known orbital period and eccentricity. Figure 8 is a diagram showing the orbit of Kepler-1704 b relative to those of Jupiter, the Solar System terrestrial planets, and HD 80606 b. The RV data also contain a slight, although tentative, acceleration ($0.0031^{+0.0029}_{-0.0027} \text{ m s}^{-1} \text{ day}^{-1}$) that possibly indicates the existence of an outer companion.

The equilibrium temperature (T_{eq}) for Kepler-1704 b as shown in Table 3 is calculated following

$$T_{\text{eq}} = T_{\text{eff}} \sqrt{\frac{R_{\star}}{2a}}, \quad (3)$$

which assumes no albedo and perfect heat redistribution (Hansen & Barman 2007). However, including a factor of $1/(\sqrt{1 \pm e})$ in this equation suggests that T_{eq} varies from $\sim 180 \text{ K}$ at apastron to $\sim 900 \text{ K}$ at periastron. This substantial $\sim 700 \text{ K}$ swing in temperature likely affects the atmosphere on Kepler-1704 b.

In the following sections, we will investigate the possibility of companions, migration history, interior composition, and

atmospheric characterization prospects for Kepler-1704 b. We take advantage of the fact that this planet’s orbital period, eccentricity, and radius are known precisely, which is remarkable for an exoplanet with its orbital properties.

4.2. Outer Companions in the Kepler-1704 System

As described in Section 1 and extensively in the broader orbital dynamics literature (e.g., Naoz 2016), the presence of an outer planetary or stellar companion may have direct consequences on the migration history of a giant planet. For Kepler-1704, archival AO imaging data yield a nondetection of stellar companions beyond ~ 100 au and upper mass limits on such a companion down to ~ 50 au (see Figure 4 and Section 2.3). In the following sections, we exploit our long baseline of RV observations to improve upon these limits with an injection-recovery test (Section 4.2.1), a RV trend analysis (Section 4.2.2), and a chaos indicator analysis (Section 4.2.3).

4.2.1. RV Injection-Recovery Test

We characterized the sensitivity of our RV data set to additional bound companions by running injection-recovery tests, in which we added synthetic signals to our RV data and converted the signal recovery rate into a map of search completeness. We used *RVSearch* (Rosenthal et al. 2021), an iterative periodogram search algorithm, to search for evidence of additional companions to Kepler-1704 b in the RV data and perform these tests. We initialized *RVSearch* with the best-fit Keplerian model for Kepler-1704 b and searched for additional companions with orbital periods spanning 2–10,000 days. We found no evidence for additional companions in this period range. Once the search was completed, *RVSearch* injected synthetic planets into the data and repeated the additional iteration to determine whether it recovered these synthetic planets. We ran 3,000 injection tests for Kepler-1704. We drew the injected planet a and $M_p \sin i$ from log-uniform distributions, and drew eccentricity from the Beta distribution with shape parameters $\alpha = 0.867$ and $\beta = 3.03$, which Kipping (2013) found represented the sample of RV-observed exoplanets. After *RVSearch* performed the injection-recovery tests, we measured search completeness across a wide range of a and $M_p \sin i$ by determining the fraction of recovered synthetic signals in localized regions of a and $M_p \sin i$.

Figure 9 shows a pair of search completeness results, one of which includes the first low-S/N RV data point (left panel) and one of which excludes it (right panel). In both cases, our RV sensitivity to companions beyond the orbital separation of Kepler-1704 b is limited, dropping below 50% completeness at $4 M_J$ beyond 4 au. The sparsity and high RMS of the RV data set drive the high lower limit on detectability in $M_p \sin i$, and the nearly 10-year observational baseline sets the sharp change in completeness around 3 au.

4.2.2. RV Trend Analysis

To build upon the injection-recovery test, we conducted a complementary analysis of acceleration (i.e., a long-term RV trend) in the Keck-HIRES RVs. This analysis focused specifically on partially sampled signals from giant planets, substellar objects, or stars that could be lurking undetected in the outer reaches of the Kepler-1704 system. When combined with a nondetection from the AO imaging, RV trends can greatly reduce the parameter space that a possible undetected companion could occupy (e.g., Crepp et al. 2012; Kane et al. 2019; Dalba et al. 2021b).

The EXOFASTv2 fit to the transit, RV, and SED (Section 3) included a parameter for “RV slope” ($\dot{\gamma}$), which quantified any acceleration measured from the RVs. As shown in Table 3, we made a low significance detection of acceleration: $\dot{\gamma} = 0.0031_{-0.0027}^{+0.0029} \text{ m s}^{-1} \text{ day}^{-1}$. To refine the mass (M_c) and orbital distance (a_c) of the companion that could have caused this RV drift, we simulated RVs over a grid of scenarios broadly following the procedure of Montet et al. (2014).

Firstly, we subtracted the maximum likelihood EXOFASTv2 solution for Kepler-1704 b from the Keck-HIRES RV data but without including the acceleration (i.e., we set $\dot{\gamma} = 0$). In doing so, we also inflated the RV uncertainties ($\sigma_{v_r}(t)$) to account for the fitted RV jitter (Table 3). The resulting RV time series ($v_r(t)$) only contained the long-term trend.

Next, we defined a logarithmically spaced 30x30 grid in companion mass ($1 M_J < M_c < 1 M_\odot$) and semi-major axis ($4 < a/\text{au} < 200$). The mass boundaries were chosen to complement the constraints from the *RVsearch* injection-recovery tests and the AO imaging (Section 2.3). The orbital distance boundaries were chosen to span the gap between the apastron distance of Kepler-1704 b and the stringent upper boundary from the AO imaging.

At each point along the M_c – a_c grid, we drew 500 sets of the orbital elements $\{\omega, e, i\}$, which are the argument of periastron, the eccentricity, and the inclination, respectively. We drew ω randomly from a uniform distribution over the interval $[0, 2\pi]$, and we drew i randomly from a uniform distribution in $\cos i$ over the interval $[0, 1]$. For e , we drew values from the Beta distribution from Kipping (2013) mentioned previously (Section 4.2.1). These random draws were meant to account for the variety of orbital configurations a massive companion could have.

Then, for each of the individual orbits, we simulated 50 sets of RV time series ($\hat{v}_r(t)$) with a cadence matching v_r . Each of the 50 sets started at a different orbital phase spaced evenly across the entire orbit. This accounted for the fact that the Keck-HIRES observations could have sampled any portion of the companion’s orbit.

Finally, we used a least-squares regression routine to minimize the familiar statistic $\chi^2 = \sum_t [v_r(t) - \hat{v}_r(t)]^2 / \sigma_{v_r}(t)^2$. This

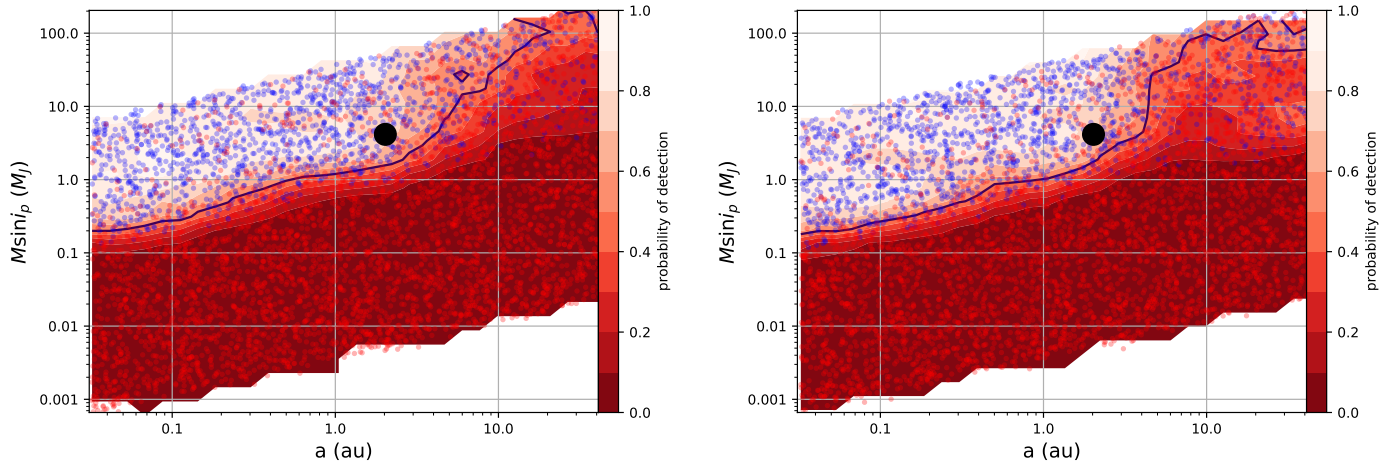


Figure 9. RVSearch injection and recovery to search for other signals in the RV data set. The left panel shows completeness contours for all RV data, while the right panel shows contours with the earliest RV data point removed (see Section 2.2). Red dots represent injected signals that were not recovered as opposed to blue dots that show recovered signals. The black dot is Kepler-1704 b, and the black line shows the 50% recovery contour.

minimization was necessary because the Keck-HIRES RVs are relative, not absolute. Assuming uncorrelated errors, we converted the $50 \chi^2$ values for each individual orbit to relative probabilities following $P \propto \exp(-\chi^2/2)$, and we summed the probabilities to effectively marginalize over the portion of the orbit captured by the data. We also summed the probabilities of the 500 sets of orbits at each grid point to effectively marginalize over all orbital properties other than M_c and a_c . Lastly, we normalized the map of probabilities such that 22.5 million probability calculations summed to unity ultimately yielding relative likelihood values. Figure 10 (left panel) shows the resulting map.

The slight acceleration detected in the full set of RVs prefers companions within roughly 30 au and less massive than a few hundred Jupiter masses although some probable solutions are still present at wide separation and high mass. Incorporating the upper mass limit from the AO imaging (Section 2.3) trims a correlated region of parameter space at the highest masses and largest orbital separations. Also, assuming that any companion with at least a 50% RVsearch recovery rate should have been detected, the trend analysis further refines the likely parameter space of a companion.

We repeated this entire analysis but after removing the first Keck-HIRES RV data point, as its timing and quality may have inaccurately affected the measured RV trend (Section 2.2). The resulting map of relative likelihoods calculated without the first RV data point is shown in the right panel of Figure 10. For context supporting the second map, we also conducted a second EXOFASTv2 fit without the first Keck-HIRES data point that was otherwise identical to the fit described in Section 3. The only appreciable difference between the two EXOFASTv2 fits was value of $\dot{\gamma}$, which decreased in significance to $-0.0002 \pm 0.0029 \text{ m s}^{-1} \text{ day}^{-1}$ in

the latter case. This difference manifests in the relative likelihood map as a preference toward larger orbits ($a \gtrsim 30$ au) rather than smaller ones. The map is again complemented by the AO imaging upper limit and the region with over a 50% RVsearch recovery rate.

Within the parameter space we are exploring, it is also helpful to consider which companions would be capable of overcoming precession caused by general relativity and exciting the eccentricity of Kepler-1704 b through Kozai–Lidov cycles. Dong et al. (2014) calculated an approximate *strength* criterion for warm Jupiters (their Equation 5) that we apply to Kepler-1704 b. In the limiting case of an initially circular orbit that is much longer-period than that of a hot Jupiter, we identify the region of M_c – a parameter space with objects that are unable to have excited the eccentricity of Kepler-1704 b (Figure 10, yellow region). By all of our other analyses, we cannot rule out the existence of a companion at the lowest masses and largest separation we consider. However, such a companion is also too low mass and orbits too far from Kepler-1704 b to overcome GR precession through Kozai–Lidov interactions.

Considering all of the companion analyses together yields three conclusions for possible outer companions in the Kepler-1704 system. Firstly, for $M_c \gtrsim 700 M_J$, we should have either recovered the signal in the Keck-HIRES RVs ($\geq 50\%$ recovery rate) or detected the source directly in the AO imaging for nearly all values of a . Secondly, for $50 \lesssim M_c/M_J \lesssim 700$, those with $a \lesssim 40$ au should have been recovered by the RV data, and those with $a \gtrsim 150$ au should have been detected in the AO imaging. A companion with separation between these values could go undetected. Thirdly, we do not have sensitivity to companions with $M_c \lesssim 50 M_J$ within ~ 150 au, so there could be substellar or planetary compan-

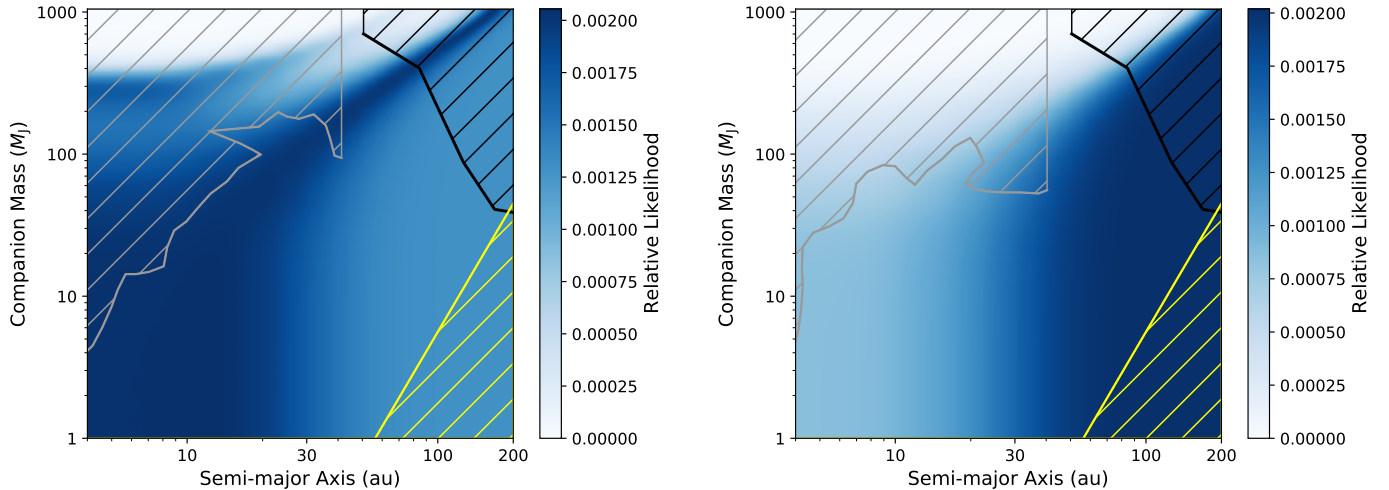


Figure 10. Relative likelihood of a companion in mass and semi-major axis space based on the acceleration in the Keck-HIRES RV residuals after the signal from Kepler-1704 b was subtracted. *Left:* Likelihoods were calculated using all Keck-HIRES RV data points. *Right:* Likelihoods were calculated after removing the first Keck-HIRES RV data point (Section 2.2). In both panels, the black hatched region (upper, right) is ruled out to 5σ by the AO imaging (Figure 4) and the yellow hatched regions (lower, right) cover companions that could not excite the observed eccentricity through Kozai–Lidov cycles (Dong et al. 2014). Any potential candidates in the gray hatched regions (upper, left) have greater than a 50% recovery rate in the corresponding RVsearch analysis (Figure 9).

ions in this region. At these masses, our RV trend analysis reveals a preference for companions with $a \gtrsim 30$ au. Although, some companions in this region of parameter space would be unable to excite the observed eccentricity of Kepler-1704 b.

4.2.3. MEGNO Simulations

To test whether additional constraints can be placed on the orbital configurations of the potential outer companion, we ran a dynamical simulation using the Mean Exponential Growth of Nearby Orbits (MEGNO) chaos indicator (Cincotta & Simó 2000). The MEGNO indicator demonstrates whether a specific system configuration would lead to chaos after a certain integration time by distinguishing between quasi-periodic and chaotic evolution of the bodies within the system (e.g., Hinse et al. 2010). The final MEGNO value returned for a specific orbital configuration is useful for determining the stochasticity of the configuration, where chaos is more likely to result in unstable orbits for planetary bodies. With a grid of orbital parameters, a MEGNO simulation can provide valuable information on the orbital configurations that are favored by dynamical simulations, and reject configurations that return chaos results.

The MEGNO simulation to explore the dynamically viable locations for various outer companions was carried out within the N-body package REBOUND (Rein & Liu 2012) with the symplectic integrator WHFast (Rein & Tamayo 2015). We used the stellar and planetary parameters from Table 2 and Table 3, respectively. We provided a linear-uniform grid in semi-major axis (20–60 au) and companion mass (1–100 M_J) that aligned with the higher likelihood re-

gion in Figure 10 (right panel). The eccentricity of the outer companion was set to zero. The simulation was integrated for 20 million years with a time step of 0.034 years (~ 12.4 days). This time step was chosen to be $1/80$ of the orbital period of Kepler-1704 b, a fourth of the recommended value (Duncan et al. 1998), to increase the sampling near the periastron passage of this highly eccentric planet. The integration was set to stop and return chaos results if any of the planetary orbits started extending beyond 100 au.

Figure 11 shows the grid of results of the MEGNO simulation. Each grid point is color-coded according to the final MEGNO value for the orbital configuration of that outer companion. A MEGNO value around 2 (green) is considered non-chaotic (Hinse et al. 2010) and is thus a dynamically viable region where the outer companion could exist without making the system chaotic. Grid points in red indicate simulations that returned chaotic results, and those in white indicate irregular events such as close encounters and collisions, all of which are unfavorable configurations for an outer companion.

Only a few stripes of parameter space contain orbital configurations that lead to chaos. The stripes indicate systems where nonlinear eccentricity secular resonances overlap leading to secular chaos (e.g., Lithwick & Wu 2011; Wu & Lithwick 2011). The stripes become less defined at wider orbits because our simulation has not been run long enough to capture the resonance evolution. Besides these narrow regions, this analysis fails to rule out any extra substantial area of parameter space where a massive companion could exist.

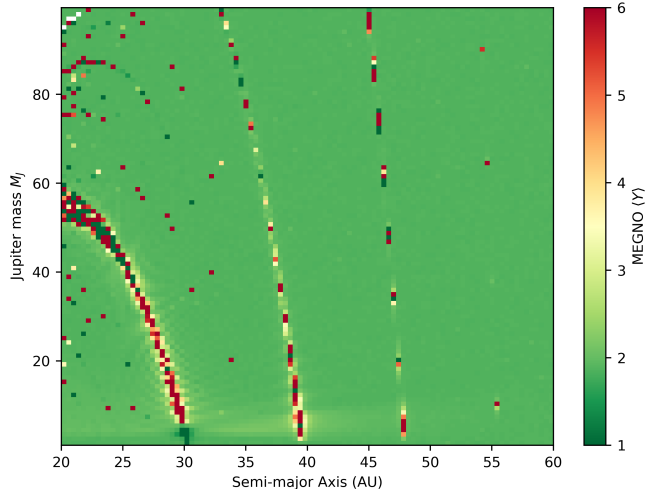


Figure 11. MEGNO simulation result with a grid of orbital configurations for the outer companion. Green regions (low values) are stable against chaos. The stripes identify chaos due to the overlap of secular resonances.

4.3. Bulk Metallicity Retrieval for Kepler-1704 b

Continuing our discussion of results, we now shift the attention from the outer reaches of the Kepler-1704 system back to Kepler-1704 b itself.

With the measured mass and radius of Kepler-1704 b, along with other system properties, we retrieved the mass of its heavy elements or its bulk metals (M_z) and calculated its bulk metallicity ($Z_p \equiv M_z/M_p$) following [Thorngren & Fortney \(2019\)](#). Briefly, we modeled the thermal evolution of Kepler-1704 b using one-dimensional structure models with a core composed of a rock–ice mixture at equal amounts, a homogeneous convective envelope made of a H/He–rock–ice mixture, and a radiative atmosphere. The atmosphere models were interpolated from the grid of [Fortney et al. \(2007\)](#). Samples were drawn from the posterior probability distributions for planet mass, radius, and age (Section 3), and the heavy element mass was adjusted in the structure models to recover the planet radius.

This analysis relied on two assumptions. First, we assumed that the planet radius is not inflated (e.g., [Laughlin 2018](#)) because the average irradiation flux received by Kepler-1704 b (see Table 3), which is well below the canonical $2 \times 10^8 \text{ erg s}^{-1} \text{ cm}^{-2}$ empirical threshold for giant planets ([Miller & Fortney 2011](#); [Demory & Seager 2011](#); [Sestovic et al. 2018](#)). Second, we neglected any internal heating from circularization tides. We assumed that tides are an inefficient means of heating Kepler-1704 b as evidenced by its tidal circularization timescale (τ_{circ}) given by Equation 3

from [Adams & Laughlin \(2006\)](#):

$$\tau_{\text{circ}} = 1.6 \text{ Gyr} \left(\frac{Q}{10^6} \right) \left(\frac{M_p}{M_J} \right) \left(\frac{M_*}{M_\odot} \right)^{-3/2} \left(\frac{R_p}{R_J} \right)^{-5} \left(\frac{a}{0.05 \text{ au}} \right)^{13/2} \quad (4)$$

where Q is tidal quality factor that is assumed to be 10^6 (similar to Jupiter). As listed in Table 3, τ_{circ} is 80,000 Gyr, much longer than the age of the universe even considering error introduced by our estimate value for Q .

The metallicity retrieval was complicated slightly by the bimodal probability distribution for age that we inferred from the comprehensive system modeling (Figure 7). Instead of using separate normal priors for stellar mass and age, we used a bivariate Gaussian kernel-density estimate. Then, we sampled the posterior with a Markov chain Monte Carlo technique.

The results of the bulk metal mass retrieval are shown in Figure 12. Despite the bimodality in age, the marginalized posterior probability distribution for bulk metallicity is a near-normal distribution at $Z_p = 0.12 \pm 0.04$, corresponding to $M_z \approx 150 M_\oplus$. To calculate the stellar metallicity (Z_*), we assumed that the iron abundance ($[\text{Fe}/\text{H}]$) scales with total heavy metal content such that $Z_* \equiv 0.0142 \times 10^{[\text{Fe}/\text{H}]}$ ([Asplund et al. 2009](#); [Miller & Fortney 2011](#)), which yields $Z_* = 0.0229 \pm 0.0031$. Finally, we calculated the bulk metallicity enrichment relative to stellar for Kepler-1704 b as $Z_p/Z_* = 5.2 \pm 1.9$.

We place the bulk metal mass and metallicity enrichment in context of other cool ($T_{\text{eq}} \lesssim 1000 \text{ K}$), weakly irradiated ($\langle F \rangle < 2 \times 10^8 \text{ erg s}^{-1} \text{ cm}^{-2}$) giant exoplanets from the [Thorngren et al. \(2016\)](#) sample⁸ in Figure 13. By metal mass and enrichment, Kepler-1704 b is entirely consistent with the known trends. Kepler-1704 b contains more metal mass than its lower-mass counterparts, but it is broadly less enriched in metals relative to its host star. These findings are consistent with the theory of core accretion as its formation scenario, followed by a period of late-stage heavy element accretion (e.g., [Mousis et al. 2009](#); [Mordasini et al. 2014](#)). Kepler-1704 b is similar to the other high-mass ($M_p \gtrsim 2 M_J$) giant planets in that it orbits a metal-rich star, something that has been predicted by population synthesis models (e.g., [Mordasini et al. 2012](#)) and likely relates to the correlation between host star metallicity and giant planet occurrence (e.g., [Gonzalez 1997](#); [Santos et al. 2004](#); [Fischer & Valenti 2005](#)).

In Figure 13 (right panel), we also include a prediction from [Ginzburg & Chiang \(2020\)](#). They model concurrent gas accretion and mergers during giant planet formation as an alternate means of explaining the heavy metal content of giant planets. The scatter in the data enclosed by the dotted black

⁸ We exclude Kepler-75 b in all related figures and analyses since [Thorngren et al. \(2016\)](#) only derived an upper limit on its metal mass.

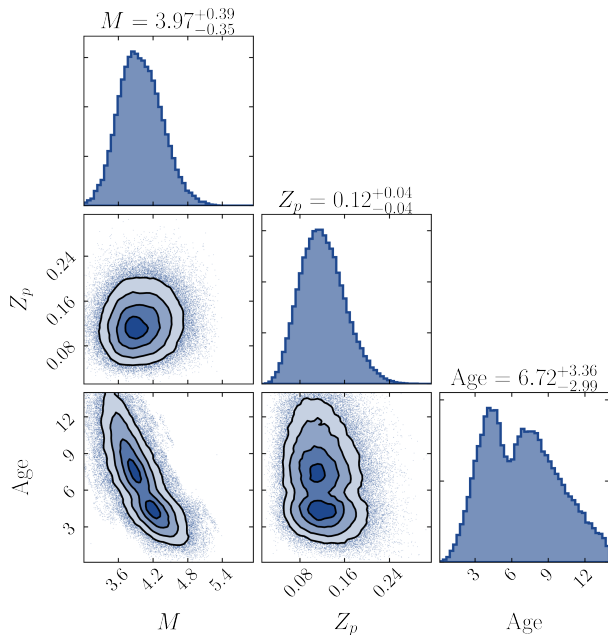


Figure 12. Posterior probability distributions from the heavy element mass retrieval for Kepler-1704 b. The symbols M and Z_p represent planet mass and bulk metallicity, respectively. Despite the bimodality in age (see Section 3), Z_p is normal. The inferred bulk metallicity of Kepler-1704 b corresponds to a heavy element mass of $\sim 150 M_{\oplus}$ and an enrichment (relative to stellar) of ~ 5 .

lines can be explained by the intrinsically chaotic nature of mergers, even if all systems evolve from nearly identical conditions as quantified by a critical core mass of $10 M_{\oplus}$. We find that the mass and bulk metallicity enrichment of Kepler-1704 b are also consistent with the theory of concurrent gas accretion and mergers.

It is interesting to consider how trends in heavy element mass, metal enrichment, and total planet mass relate to other orbital and stellar properties. In Figure 14, we show the relative residuals (calculated/best fit) of heavy element mass and metallicity enrichment relative to stellar as a function of eccentricity for the Thorngren et al. (2016) sample of weakly irradiated giant exoplanets and Kepler-1704 b. As noted by Thorngren et al. (2016), there is no discernible trend in either quantity. However, given how sparsely populated the high-eccentricity region is, it is worthwhile to consider the (now) five systems with $e > 0.6$ individually. The residual heavy element mass and metallicity enrichment of Kepler-1704 b and HD 80606 b are nearly identical, as are their orbital eccentricity and planet mass. However, HD 80606 b likely migrated via secular perturbations with HD 80607 (e.g., Wu & Murray 2003; Fabrycky & Tremaine 2007; Winn et al. 2009) whereas we are unsure if similar interactions with a planetary or stellar companion have influenced the migration history of Kepler-1704 b. If Kepler-1704 b and HD 80606 b followed different migration pathways, there is no evidence in

their bulk metallicity to distinguish them. The residual heavy element mass and the metallicity enrichment of these two planets are significantly different than those of HD 17156 b, which has $e \approx 0.67$ (Fischer et al. 2007; Bonomo et al. 2017). Unlike HD 80606 b, HD 17156 b has no stellar companion and its orbit is nearly aligned with its host star (Cochran et al. 2008; Narita et al. 2008; Barbieri et al. 2009). Also, HD 17156 b’s orbital period is almost two orders of magnitude shorter than that of Kepler-1704 b. Therefore, it is perhaps not surprising that these planets experienced different formation histories that could account for the metallicity differences. The final two high-eccentricity planets in Figure 14 (KOI-1257 b and Kepler-419 b) have relatively imprecise residual heavy element masses and metallicity enrichments. KOI-1257 b is thought to be in a binary star system, possibly pointing to Kozai migration (Santerne et al. 2014). On the other hand, Kepler-419 b is joined by a massive outer giant planet that has a low mutual inclination, such that Kozai migration is likely not a viable migration theory (Dawson et al. 2014). The overall lack of a clear trend between heavy element mass or metallicity enrichment and the presence of a companion and/or high stellar obliquity is likely in part a result of the small number of data points. However, it could also suggest that the heavy element accretion occurs before or independently from the various channels of eccentricity excitement.

4.4. Atmospheric Characterization Prospects for Kepler-1704 b

The bulk heavy element mass retrieval suggested that ~ 150 Earth-masses of metals should exist within Kepler-1704 b. The distribution of those heavy elements within the planet can possibly affect the composition of its atmosphere. Specifically, Thorngren & Fortney (2019) showed that the bulk metallicity places an upper limit on atmospheric metallicity. For Kepler-1704 b, the core-free 2σ upper limit ($Z_p = 0.2$) for atmospheric metallicity is $35.7\times$ solar. A natural next step in the exploration of Kepler-1704 b is to test this prediction via atmospheric characterization.

Considering only orbital period or semi-major axis, Kepler-1704 b is a rare opportunity for transmission spectroscopy (Seager & Sasselov 2000). Although, long-period exoplanets pose specific challenges to this kind of technique. Not only are transits of such planets geometrically rare, but their timing is often uncertain. Since only two transits of Kepler-1704 b have been observed, the presence of extreme transit timing variations (TTVs; Wang et al. 2015b) cannot be ruled out (e.g., Dalba & Muirhead 2016; Dalba & Tamburo 2019, see Section 5.3). Furthermore, atmospheric temperature will (to first order) decrease with increasing orbital distance. As a result, atmospheres will be cooler and scale heights and transmission spectrum features will be smaller.

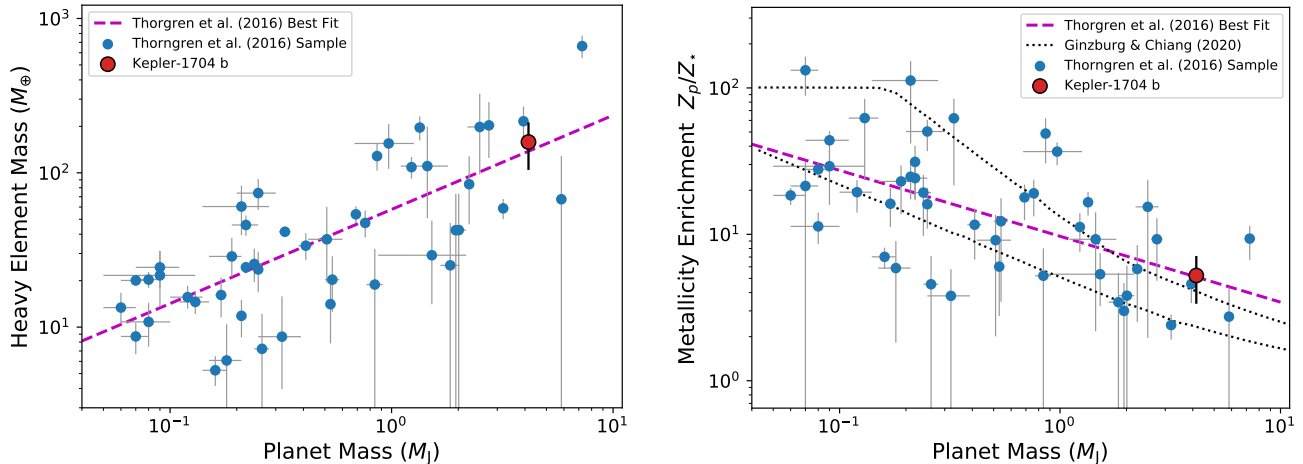


Figure 13. *Left:* Heavy element mass of the weakly irradiated giant exoplanets from [Thorgren et al. \(2016\)](#) as well as Kepler-1704 b. *Right:* Metallicity enrichment of the weakly irradiated giant exoplanets from [Thorgren et al. \(2016\)](#) as well as Kepler-1704 b. The dotted black lines show the scatter that can be accounted for by concurrent gas accretion and mergers assuming a critical core mass of $10 M_{\oplus}$ at the onset of runaway gas accretion ([Ginzburg & Chiang 2020](#)). The position of Kepler-1704 b in these panels is consistent with substantial late-stage accretion of heavy elements or core growth through mergers during gas accretion.

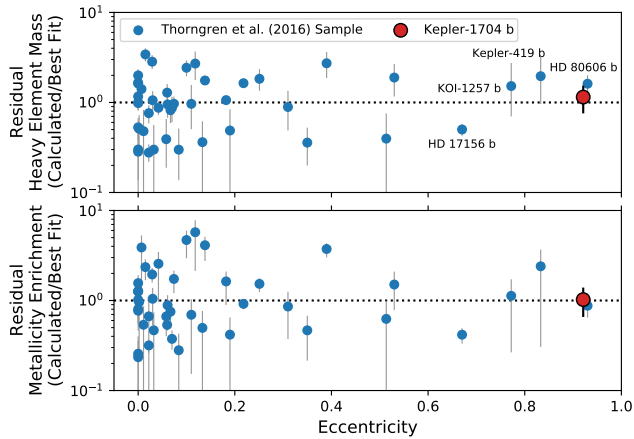


Figure 14. Relative residuals (calculated/best fit) of the heavy element mass (top) and the metallicity enrichment relative to stellar (bottom) as a function of eccentricity for the [Thorgren et al. \(2016\)](#) sample of weakly irradiated giant exoplanets and Kepler-1704 b.

Surprisingly, this can be balanced by low surface gravity, as would be the case if Saturn was subject to transmission spectroscopy ([Dalba et al. 2015](#)). The transiting geometry of the long-period Kepler-1704 b also makes it a unique candidate for testing theories of atmospheric refraction (e.g., [Sidis & Sari 2010](#); [Dalba 2017](#); [Alp & Demory 2018](#)) that have not yet been observationally tested ([Sheets et al. 2018](#)).

However, considering the large radius of the subgiant Kepler-1704 and the high mass of Kepler-1704 b, this system is a challenging target for transmission spectroscopy. With a surface gravity of 86 m s^{-2} and the average equilibrium temperature of 254 K from [Table 3](#) (assuming no albedo), the atmospheric scale height is only $\sim 12 \text{ km}$, which corresponds to 1 part-per-million (ppm) in the transmission spectrum. The

out-of-transit stellar mirage caused by refraction also scales with the atmospheric scale height, making such a detection similarly difficult (e.g., [Dalba 2017](#)).

On the other hand, we used [Equation 3](#) to estimate that T_{eq} at periastron, which is within several days of transit, is $\sim 900 \text{ K}$. This suggests a $3.6\times$ increase in the atmospheric scale height and transmission spectrum feature size. Although 4 ppm is still beyond the reach of current and future facilities, we caution that our intuition for predicting favorable transmission spectroscopy targets is largely based on our current understanding of hot, close-in exoplanet atmospheres. This possibly warrants skepticism. If Saturn were a transiting exoplanet, its warm stratosphere and active photochemistry would produce a $\sim 90 \text{ ppm}$ absorption feature in its transmission spectrum at $3.4 \mu\text{m}$ ([Dalba et al. 2015](#)). Considering only Saturn’s T_{eq} as defined in [Equation 3](#) would under predict its amenability to transmission spectroscopy. Other long-period giant exoplanets may prove surprising as well.

Even if transmission spectroscopy is not a viable atmospheric characterization technique, the 0.16 au periastron distance of Kepler-1704 b caused by its extreme eccentricity possible qualifies it for an IR phase curve analysis.

4.4.1. IR Phase Curve Analysis

To predict the expected thermal signature of the planet during periastron passage, we calculated the IR phase curve for Kepler-1704 b during one complete orbital period. These calculations followed the methodology of [Kane & Gelino \(2011\)](#) using the stellar and planetary parameters provided in [Tables 2 and 3](#), respectively. We assumed a passband of $4.5 \mu\text{m}$, a Bond albedo of zero, and we calculated the flux ratio of planet to star using the “hot dayside” and “well mixed” models. These models represent the extremes of heat redistribri-

butions as they assume re-radiated energy over 2π and 4π sr, respectively. The full IR phase curve for both models are shown in Figure 15, along with a zoomed panel that shows the location of the periastron passage.

There are several caveats to this calculation. We assumed an instantaneous response of the planetary absorption and IR emission, whereas the radiative and advective time scales will determine the nature of phase lags in thermal emission profiles (Langton & Laughlin 2008; Cowan & Agol 2011a). This, combined with the blackbody emission and zero albedo assumptions, means that the calculations presented in Figure 15 may be considered as an upper limit on the expected IR emission. Furthermore, the variation in temperature would also alter the atmospheric composition. Some of the energy would be converted into latent heat to dissociate larger molecules or particulates. There would also be an interconversion between CO and CH₄ (e.g., Visscher 2012). The timescale of this reaction, and also the vertical mixing timescale, should be considered to produce a more accurate model of the phase curve. We leave these considerations for a future work and instead derive a first-order, upper limit on the phase curve emission.

Despite the various assumptions that apply to this phase curve modeling, the order of magnitude ($\mathcal{O}(10^2)$ ppm) of the thermal flux increase is likely accurate. Several instruments onboard *JWST* will have sensitivity in the near- to thermal-IR and, based on preliminary noise floor expectations (Greene et al. 2016), should be capable of detecting the Kepler-1704 b phase variation. Borrowing from solar system intuition, 4–6 μm is likely a promising wavelength for such an observation. Jupiter and Saturn’s atmospheres have low opacity in this wavelength region that exists between bands of methane and phosphine where radiation from 5–8 bars can escape (Irwin et al. 2014). Jupiter’s radiance near 5 μm even exceeds that at mid-IR wavelengths (e.g., Irwin et al. 1998; Fletcher et al. 2009a; Irwin et al. 2014).

The periastron passage of Kepler-1704 b occurs over ~ 10 days and includes the transit. Low cadence time series observations from the F444W filter of NIRCcam, for example, could detect the peak flux ratio and the width of the feature assuming that the visit-to-visit photometric variability does not overwhelm the astrophysical signal. Including at least one high cadence, longer visit at or following periastron would also be valuable because the phase curve may exhibit “ringing” as the hot spot from periastron rotates in and out of view (e.g., Cowan & Agol 2011b). This effect is not featured in our simulation of Kepler-1704 b, which assumed pseudo-synchronous rotation (Hut 1981). However, given the inefficiency of tides at the periastron distance of Kepler-1704 b, this assumption may be an oversimplification. The detection of a ringing oscillation in the IR phase curve would test this

assumption and possibly directly yield the effective planetary rotation rate.

The detectability of the thermal phase curve for Kepler-1704 b should be explored in more detail with an atmospheric structure code (e.g., Mayorga et al. 2021). Such an effort is beyond the scope of this paper and should likely wait until *JWST* is launched and commissioned. In addition to a broadband detection of phase variability, the prospects for spectroscopic detection should also be investigated. Transmission spectroscopy may not be an effective tool to measure atmospheric composition (e.g., metallicity), so any other possible method would be extremely useful. Atmospheric metal enrichment (relative to stellar) is a specifically valuable property to measure because it can be compared to the planet’s bulk metallicity enhancement (Section 4.3). One prediction would be an atmospheric metallicity less than the bulk metallicity if some heavy elements comprise a planetary core or there is otherwise an increasing gradient in metals with depth. However, for Jupiter and Saturn, recent high-precision gravity data and well established atmospheric composition results suggest a more complicated picture (Niemann et al. 1998; Wong et al. 2004; Fletcher et al. 2009b; Wahl et al. 2017; Guillot et al. 2018; Iess et al. 2019; Müller et al. 2020b). More elaborate theories including inverse compositional gradients (e.g., Debras & Chabrier 2019) are needed to explain Jupiter and Saturn and could possibly be refined through atmospheric characterization of exoplanets like Kepler-1704 b.

Based on the optimistic prospect of *JWST* observations, we determined the timing of transits and periastron passages of Kepler-1704 b occurring in the next 10 years (Table 4). For each event, we checked for visibility from *JWST* using the General Target Visibility Tool⁹. This tool only predicts visibility through the end of 2023, but we assumed the same visibility of Kepler-1704 in later years. The 2023 transit of Kepler-1704 b will not be visible to *JWST* but the 2028 transit will be visible. The 2025 transit will occur within 24 hr after the visibility window closes and the 2031 transit will occur roughly six days after the visibility window opens. If the solar avoidance restrictions change after launch, these transits may or may not be visible to *JWST*. The periastron passage of Kepler-1704 b occurs several hours before transit, so its visibility is similar. However, as shown in Figure 15, the peak of the thermal flux ratio spans ~ 10 days. Even if the exact moment of periastron is (or is not visible), some portion of the event is expected to be visible to *JWST*.

4.4.2. Radio Emission

⁹ Accessed 2021 February 11 (https://github.com/spacetelescope/jwst_gtvt).

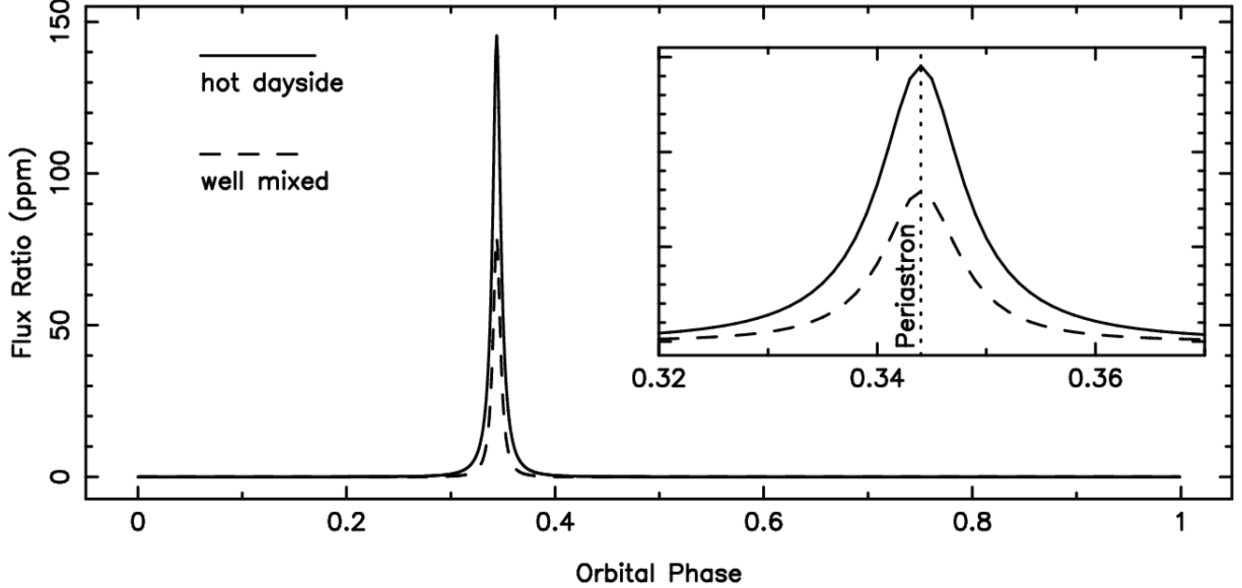


Figure 15. Simulated $4.5 \mu\text{m}$ phase curve of Kepler-1704 b following Kane & Gelino (2011). The “hot dayside” and “well mixed” models correspond to atmospheric heat redistribution efficiencies of 0 and 1, respectively. The ~ 100 ppm amplitude of this variation is favorable for *JWST* observation. This simulation assumed a pseudo-synchronous rotation of Kepler-1704 b. If the planet’s rotation is not synchronized, an oscillation in flux at the frequency of the planets effective rotation rate may also be detectable.

Table 4. Future Transit and Periastron Timing Predictions

Epoch ^a	Conjunction (Transit) Time		Periastron Time		<i>JWST</i>
	BJD _{TDB}	UTC	BJD _{TDB}	UTC	Visibility ^b
5	2460016.0902±0.0046	2023-03-12 14:10	2460015.78 ± 0.20	2023-03-12 06:37	None
6	2461004.9714±0.0055	2025-11-25 11:19	2461004.66 ± 0.20	2025-11-25 03:46	Partial
7	2461993.8525±0.0065	2028-08-10 08:28	2461993.54 ± 0.20	2028-08-10 00:55	Full
8	2462982.7336±0.0074	2031-04-26 05:36	2462982.42 ± 0.20	2031-04-25 22:03	Partial

The times listed here do not account for possible uncertainty owing to yet undiscovered TTVs (see Section 5.3).

^a Epoch=0 is defined as the first transit observed by the *Kepler* spacecraft.

^b *JWST* visibility after 2023 December 31 is based on previous years’ visibility. Epochs for which the full periastron passage of Kepler-1704 b partially falls outside of the predicted visibility windows are labeled as “Partial” (see the text).

Unlike for transmission spectroscopy, the relatively high mass of Kepler-1704 b is beneficial to attempts to measure planetary radio emission. Lazio et al. (2010) searched for radio emission from HD 80606 b during a periastron passage but measured only an upper limit. That experiment was based on the expectation that the variation in planet–star distance over an eccentric orbit would lead to dramatic increase in magnetospheric emission. Assuming that luminosity scales with the planet–star distance as $L \propto d^{-1.6}$ (e.g., Farrell et al. 1999), then the factor of 24.3 change in distance for Kepler-1704 b would produce a 165x increase in luminosity. While this is slightly smaller than the 200x increase expected for HD 80606 b, a future radio search may be aided by the fact that Kepler-1704 b can possibly emit at higher frequencies.

We estimate that the upper limit emission frequency as determined by the local plasma frequency in the emission region for Kepler-1704 b is

$$\nu = 24 \text{ MHz} \left(\frac{\Omega}{\Omega_J} \right) \left(\frac{M_p}{M_J} \right)^{5/3} \left(\frac{R_p}{R_J} \right)^3 \quad (5)$$

where Ω is the angular rotation rate (Farrell et al. 1999; Lazio et al. 2004, 2010). In this Equation, all values are scaled to those of Jupiter. For HD 80606 b, tidal forces are expected to force the planet into pseudo-synchronous rotation with a period of 39.9 hr (Hut 1981; Lazio et al. 2010). It is unlikely that this would also apply to Kepler-1704 b, for which the larger periastron distance renders tides inefficient. Therefore, the assumption of a Jupiter-like rotation period

(~ 9.9 hr) is reasonable. In that case, evaluating Equation 5 gives 310 MHz. Lazio et al. (2010) argued that this equation may actually under-predict the cutoff frequency of exoplanets, as it does for Jupiter, and suggested that the upper limit may be 60% larger. In that case, the cutoff frequency for Kepler-1704 b would be 497 MHz, which is more accessible to existing radio observatories than HD 80606 b’s 55–90 MHz.

A full simulation of the potential for radio emission from Kepler-1704 b is beyond the scope of this paper, and the ability to make such a detection, at least relative to previous attempts for HD 80606 b, will likely be hindered somewhat by the greater distance to the Kepler-1704 system. However, even our approximate calculation suggests that Kepler-1704 b is one of the best systems to investigate magnetospheric response to a rapidly changing planet–star distance. Such an observation stands to extend the study of giant exoplanet magnetic fields beyond the inner most hot Jupiters (e.g., Cauley et al. 2019) and explore magnetic field generation in planets akin to Jupiter and Saturn.

5. DISCUSSION

Much of the previous analysis has focused on key pieces of information that inform the formation and migration history of Kepler-1704 b. Orbital period and eccentricity are two of the most notable properties in this respect. As shown in Figure 16, these properties place Kepler-1704 b among a small group of known exoplanets on long-period, highly eccentric orbits that are useful for testing the extremes of planetary formation theories. More remarkable, though, is the transiting geometry of the orbit of Kepler-1704 b. Relative to other transiting exoplanets, the position of Kepler-1704 b in a – e space is unrivaled (Figure 16). Kepler-1704 b thereby offers its radius and bulk composition, as well as its orbital properties, as clues to its formation and migration history.

Here, we assemble all of this information into a coherent narrative describing the history of this interesting planet.

5.1. Kepler-1704 b: The Failed Hot Jupiter

Based solely on the measured orbital eccentricity, we discard disk-migration as the explanation for the orbital properties of Kepler-1704 b. Papaloizou et al. (2001) showed that eccentricities up to ~ 0.25 could be achieved through disk interactions for a variety of planet masses. Although, eccentricity is generally damped by the disk for giant planets with $M_p < 5 M_J$ (Bitsch et al. 2013). Recent work revisiting disk cavity migration argued for eccentricities up to 0.4 for giant planets (Debras et al. 2021), which is possibly a viable theory for other outer giant planets like Kepler-1514 b ($e = 0.401^{+0.013}_{-0.014}$), which also harbors an inner Earth-sized companion (Dalba et al. 2021a). Explaining the current orbit of Kepler-1704 b, however, requires excitation to high eccentricity by another body.

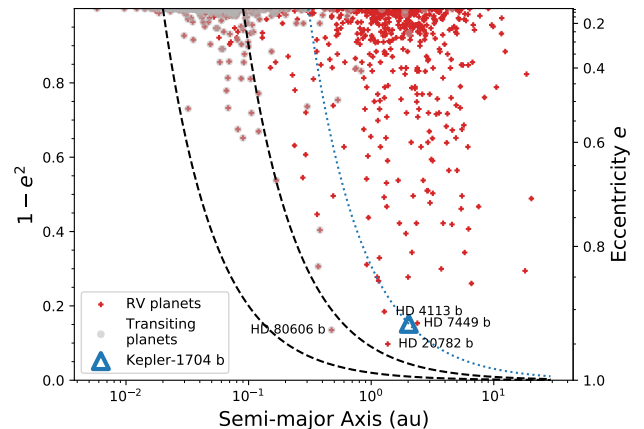


Figure 16. The eccentricity for all non-controversial exoplanets with known a (or with the necessary parameters to calculate a) and with (minimum) mass greater than $0.3 M_J$ as listed in the NASA Exoplanet Archive (accessed 2021 February 17). The marker style indicates whether a planet has been detected by transits and/or RVs. The dashed black lines indicate tracks of constant angular momentum with final orbital periods of 1 and 10 days. The dotted blue line indicates the track for Kepler-1704 b.

Through multiple analyses, we rule out stellar companions with mass greater than $\sim 700 M_J$ at most orbital separations in the Kepler-1704 system. As described in Section 4.2, undetected less massive companions may still be present at a variety of separations and could have driven Kepler-1704 b to its high eccentricity through secular Kozai–Lidov perturbations (e.g., Wu & Murray 2003; Naoz et al. 2011). Also, star-planet Kozai migration from a stellar companion that was present when Kepler-1704 b formed but subsequently lost due three-body interactions also remains a possible explanation. However, motivated by our nondetection of a companion and only a tentative detection of acceleration in ~ 10 years of RV measurements, we discard secular perturbations as being the most likely explanation for the high eccentricity of Kepler-1704 b. We recommend that future dynamical simulations explore the areas of parameter space that we have not ruled out to see if a hidden companion could theoretically explain the properties of Kepler-1704 b (c.f., Jackson et al. 2019).

This brings us to eccentricity excitation theories involving close, fast dynamical interactions. Specifically, could planet-planet scattering (e.g., Rasio & Ford 1996) provide an explanation for the eccentricity of Kepler-1704 b? Many aspects of the observed eccentricity distribution of giant exoplanets can be explained by planet-planet scattering (e.g., Moorhead & Adams 2005; Chatterjee et al. 2008; Raymond et al. 2010; Bitsch et al. 2020), including planets with eccentricities above 0.99 (Carrera et al. 2019). For Kepler-1704 b, we find planet-planet scattering is consistent with its orbital properties, its host star, and its bulk interior proper-

ties. Kepler-1704 is metal-rich ($[\text{Fe}/\text{H}] = 0.196 \pm 0.057$ from Table 2). Dawson & Murray-Clay (2013) demonstrated that metal-rich stars tend to host high-eccentricity hot Jupiters, which they interpreted as evidence support HEM by planet-planet scattering owing to the well know correlation between stellar metallicity and giant planet occurrence (e.g., Santos et al. 2004; Fischer & Valenti 2005). Even though Kepler-1704 b is not a hot Jupiter, it is reasonable that it could have formed alongside other giant planets that were subsequently scattered. After many close encounters, possibly even tens of thousands (Carrera et al. 2019), Kepler-1704 b could have been driven to its current eccentricity. However, its final periastron distance was too far for tides to efficiently circularize the orbit, leaving Kepler-1704 b as the failed hot Jupiter that we have characterized here.

Now, we consider this migration pathway in the context of the bulk heavy metal mass, which we found to be $\sim 150 M_{\oplus}$. This enrichment could have been acquired through late-stage accretion of planetesimals or core mergers with concurrent gas accretion (Section 4.3). For the former explanation, Shibata et al. (2020) found that migrating giant planets can capture tens of Earths masses worth of planetesimals that may otherwise not be available *in situ* (e.g., Shibata & Ikoma 2019). The amount of heavy elements accreted scales with increasing migration distance and decreasing migration timescale, both of which are expected for eccentricity excitation through planet-planet scattering. However, Shibata et al. (2020) also found that the most enriched giant exoplanets, containing more than $\sim 100 M_{\oplus}$ of heavy elements likely require an additional source of enrichment.

The latter explanation mentioned above for how Kepler-1704 b acquired its heavy metal mass involves the merger of cores during gas accretion (Ginzburg & Chiang 2020). The interaction of cores during this stage of giant planet formation, while gas is still present in the disk, is broadly consistent with the high eccentricity of Kepler-1704 b. Bitsch et al. (2020) found that such scattering events at this stage are common, and systems that start with more planetary embryos create giant planets with higher eccentricities so long as the damping rates for inclination and eccentricity are slow. Indeed, slow rates are required to reproduce the eccentricity distribution of the known giant planets (Bitsch et al. 2020). It is therefore possible that the same processes that led to the accretion of heavy elements for Kepler-1704 b also contributed to exciting its eccentricity. In reality, owing to the fact that planet mergers (or collisions) are less efficient at producing high eccentricities than scattering events (e.g., Ford & Rasio 2008; Jurić & Tremaine 2008; Anderson et al. 2020), some combination of the aforementioned theories along with planet-planet scattering after the dispersal of the gas disk likely produced the Kepler-1704 system as seen today.

Moving forward, it would be useful to compare this proposed formation history to other well characterized long-period transiting giant planets. It will be particularly interesting to compare the bulk interior properties of giant planets in systems with and without outer companions that could have induced Kozai migration. If bulk heavy element composition and migration mechanisms are linked, as may be the case for Kepler-1704 b, we might expect to find a correlation between interior properties, orbital properties, and the existence of companions.

5.2. Stellar Obliquity

A critical missing piece in our discussion of the migration of Kepler-1704 b is the stellar obliquity. A substantially misaligned orbit of Kepler-1704 b would warrant a reexamination of Kozai eccentricity oscillations, although planet-planet scattering can also cause misaligned orbits (e.g., Chatterjee et al. 2008; Naoz et al. 2012). Moreover, the effective temperature of Kepler-1704 makes this system a perfect laboratory for testing the theory that hot Jupiters preferentially realign cool stars (e.g., Winn et al. 2010; Schlaufman 2010). The effective temperature of Kepler-1704 is 5745^{+88}_{-89} K, which is well below the ~ 6200 K Kraft break (Kraft 1967) that has been implicated by hot Jupiter obliquity observations. Since tidal forces are inefficient for failed hot Jupiters like Kepler-1704 b, we would expect that these planets would show a variety of obliquities and would not be preferentially aligned like hot Jupiters orbiting similarly cool stars.

In theory, the obliquity between Kepler-1704 b and its host star could be measured through the Rossiter–McLaughlin (RM) effect (Rossiter 1924; McLaughlin 1924). If successful, it would stand as the longest-period planet, by far, to have an obliquity measurement. In practice, an RM experiment will be challenging. Our SpecMatch analysis (Section 2.2) inferred a low stellar rotational velocity of $2.74 \pm 1.0 \text{ km s}^{-1}$. By Equation 40 of Winn (2010), the maximum expected amplitude of the RM effect is only 11 m s^{-1} . Assuming 30 minute exposure times (as used for the current RV data), this would only allow 12 data points across the entire transit. With the $\sim 7 \text{ m s}^{-1}$ RV precision achieved using the best-match template (see Table 1 and Section 2.2), any detection of obliquity would likely be marginal. We recommend that any future effort to observe the spectroscopic transit of Kepler-1704 b should first acquire a high-S/N spectral template of Kepler-1704 to reduce the internal RV precision by several m s^{-1} . Owing to the extreme eccentricity and the argument of periastron, the transit duration is short enough that a fortunately timed transit could be observed from a single site. For the Keck I telescope, only the second half of the 2023 transit (Table 4) is visible. Kepler-1704 will rise above the Nasmyth deck at Keck I at a favorable airmass of

~ 1.5 around 14:30 UTC on 2023 March 12. Again assuming 30 minute exposure times, that would place roughly 6 data points across the second half of RM signal. Even with the actual template and improved internal precision, a detection of obliquity would likely be moderate at best. It is not until 2028 that the Keck I telescope has the optimal position for an RM detection. The mid-transit time of the August 2028 transit is almost perfect timed with Kepler-1704 crossing the meridian, and the full transit (plus post-transit baseline) is observable. However, in the coming years, new precise RV facilities with the capability of achieving few m s^{-1} precision on faint ($V = 13.4$) stars such as MAROON-X (Seifahrt et al. 2018) or the Keck Planet Finder (Gibson et al. 2016) should consider conducting RM measurements of long-period *Kepler* planets like Kepler-1704 b.

5.3. A Third Transit of Kepler-1704 b to Explore TTVs

With only two transit events detected by *Kepler*, we cannot rule out large TTVs that could possibly preclude future transit observations (e.g., Wang et al. 2015b). TTVs of this nature would require a massive perturber with an orbit that is sufficiently close to Kepler-1704 b to allow for gravitational interaction. The RV observations presented here largely rule out such a companion on orbits interior to Kepler-1704 b (Figure 9). However, giant planet companions on wider orbits could be present. One avenue of future work would be to apply the companion limits and stability results described here to a dynamical analysis of the Kepler-1704 system to set limits on TTV magnitudes.

Another avenue toward addressing this issue would be to observe a third transit. As has been done with Kepler-421 b (Dalba & Muirhead 2016), Kepler-167 e (Dalba & Tamburo 2019), and HIP 41378 f (Bryant et al. 2021), Kepler-1704 can be observed for a window of time surrounding the expected third transit according to a linear ephemeris. For this experiment, a missed transit places a lower limit on transit-to-transit timing variations. The ground-based observability of future Kepler-1704 b transits is not as restrictive as that described for *JWST* in Section 4.4.1. For example, in March 2023, Kepler-1704 rises to reasonable elevations in the last few hours of the night in the Northern hemisphere. Any single site will likely struggle to detect the full transit. However, detections of ingress and egress from multiple sites spread out in longitude would refine the ephemeris of Kepler-1704 b and identify any TTVs.

5.4. Comparison to the Kepler-167 System

Kepler-1704 represents an interesting comparison for the Kepler-167 system, in which an early K dwarf star hosts three inner super-Earth-sized planets and an outer transiting Jupiter-analog on a $P = 1071$ day orbit (Kipping et al. 2016). Although the mass of Kepler-167 e—the outer giant planet—

has not been measured, its orbital eccentricity has been constrained to ~ 0.06 by the transit shape and duration. This low eccentricity combined with the presence of multiple inner super-Earth planets suggests that the migration mechanism for Kepler-167 e was likely gentle and driven by interactions with the disk. Kepler-167 is solar metallicity, if not slightly metal poor, so it is possible that Kepler-167 e was the only giant planet formed in the outer disk, so scattering events never occurred. Dalba & Tamburo (2019) ruled out the existence of TTVs in the ephemeris of Kepler-167 e, which further implied a lack of an outer massive companion. A mass and bulk metallicity measurement for Kepler-167 e would provide an interesting comparison with Kepler-1704 b, which likely experienced dynamical interactions with other bodies during and/or after its formation.

5.5. Could Kepler-1704 b Host Exomoons?

Giant transiting exoplanets with multi-year orbital periods are possibly exciting targets for dedicated exomoons searches (e.g., Kipping et al. 2012a; Heller et al. 2014; Teachey & Kipping 2018). Now that we have measured the mass and orbital properties of Kepler-1704 b, the plausibility of this planet hosting a system of exomoons should be investigated in more detail. Given the suspected active dynamical formation history of Kepler-1704 b, its ability to have maintained a system of exomoons is perhaps questionable. Indeed, the investigation of exomoon stability under tidal forces (e.g., Barnes & O’Brien 2002; Adams & Bloch 2016; Sucerquia et al. 2020), planet-planet scattering (e.g., Nesvorný et al. 2007; Gong et al. 2013; Hong et al. 2018), disk torques (e.g., Namouni 2010; Spalding et al. 2016), and secular migration owing to a stellar companion (e.g., Martinez et al. 2019; Trani et al. 2020) are active areas of theoretical research. Although any such study is beyond the scope of this work, we can approximate the Hill radius of Kepler-1704 b at periastron (where it is smallest):

$$r_{\text{H,peri}} \approx a(1-e) \left(\frac{M_p}{3M_\star} \right)^{1/3}. \quad (6)$$

For Kepler-1704 b, we find that $r_{\text{H,peri}} \approx 2.6 \times 10^6$ km. Any exomoon on a circular prograde orbit around Kepler-1704 b would need a semi-major axis less than (roughly) half of this value to survive the close periastron passages (Hamilton & Burns 1991). For perspective, the semi-major axis of Callisto, Jupiter’s most distant Galilean moon, is roughly 1.9×10^6 km. Of course, this calculation neglects all of the processes that led to Kepler-1704 b reaching its current orbital configuration. We offer Kepler-1704 b as a potentially interesting case study for more detailed investigations of exomoon formation and stability in the future.

The fact that Kepler-1704 b swings through its host star’s habitable zone on its eccentric orbit is also potentially inter-

esting from an exomoon standpoint (e.g., Heller 2012; Heller & Barnes 2013; Hill et al. 2018). However, the plausibility of life developing on an exomoon that experiences such intense variation in stellar irradiation should be thoroughly scrutinized.

5.6. One Path Forward for Giant, Long-period Transiting Exoplanets

The vast majority of known giant planets on au-scale orbits have unknown radii because they either do not transit or they are not known to transit. Without a radius, subsequent investigations of atmospheres and interiors are uncertain if not altogether impossible. Measuring the masses of the modest sample of known transiting giant planets with au-scale orbits and discovering more such planets will be important to advancing our understanding of giant planet formation and migration. These discoveries will also drive new theoretical advances in giant planet interiors, which are needed given that changing model assumptions can substantially alter our conclusions about the interior structures of giant exoplanets (e.g., Müller et al. 2020a).

Only a handful of outer giant exoplanets like Kepler-1704 b exist within the *Kepler* sample and they all orbit relatively faint stars. This creates two problems. Firstly, their limited number means that unfortunate transit timing (see Table 4 and also Dalba & Tamburo (2019)) can drastically slow progress to obtain new observations and advance our theoretical understanding. Secondly, their faintness must be overcome (if at all possible) by larger investments of highly competitive telescope time.

The Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015), which is actively searching for transits of bright stars around the entire sky, presents solutions to both problems. The only drawback is the tendency of TESS’s observing strategy to yield single transit events for most planets with orbital periods greater than a couple dozen days (e.g., Gill et al. 2020; Dalba et al. 2020b; Díaz et al. 2020; Lendl et al. 2020). If the *Kepler* mission had adopted the TESS mission’s observing strategy, not only would Kepler-1704 b have been identified through a single transit, but its 6 hr transit duration could have easily been misconstrued as corresponding to a relatively short orbital period. This suggests (and more quantitative efforts have shown; Cooke et al. 2018; Villanueva et al. 2019) that given enough time and targets, TESS will identify transits from a unprecedented sample of long-period giant planets. Yet, the advancement of giant planet theory and understanding will rely on continued challenging follow-up efforts to characterize these planets masses, orbits, interiors, and atmospheres.

6. SUMMARY

We obtained nearly 10 years of RV observations of the ~ 5750 K subgiant star Kepler-1704, which was found to

host a transiting giant planet candidate (KOI-375.01, now Kepler-1704 b) by the primary *Kepler* mission. Our observations and analyses confirmed the genuine nature of this exoplanet, now known as Kepler-1704 b, which is a 4.15-Jupiter-mass planet on a 988.88 day orbit with an extreme $0.921^{+0.010}_{-0.015}$ eccentricity. We performed an AO imaging analysis, interior and atmosphere modeling, and dynamical simulations to characterize this system and make predictions for future observations. The primary results of this work are as follows.

1. We collected 14 RV measurements (Table 1) of Kepler-1704 from Keck-HIRES spanning 9.6 years that confirm the 988.88 day orbital period for Kepler-1704 b, thereby ruling out the possibility of a third transit occurring in a *Kepler* data gap (Section 2.1). The RVs also confirmed the extremely high orbital eccentricity ($e = 0.921^{+0.010}_{-0.015}$) that was suspected from our photoeccentric effect modeling (Section 2.1.1) and measured the planet mass to be $4.15 \pm 0.29 M_J$. Kepler-1704 b has the longest apastron distance (3.9 au) of any confirmed transiting exoplanet with a precisely known orbital period. Moreover, we found that between periastron and apastron, the equilibrium temperature of Kepler-1704 b varies from ~ 180 K to ~ 900 K.
2. Archival AO imaging of Kepler-1704 from the PHARO instrument identified three possible stellar companions within $\sim 10''$, two of which were previously published (Wang et al. 2015a). We found that two of the companions are spurious sources and the third is not gravitationally associated (Section 2.3). Additional archival AO imaging from the NIRC2 instrument (Furlan et al. 2017) yielded a nondetection of stellar companions within $2''$ and placed upper limits on the mass of any undetected companion within 1,000 au of Kepler-1704 (Figure 4).
3. The joint analysis of transit, RV, and broadband photometry (Section 3) identified a bimodality in stellar properties due to the evolutionary state of Kepler-1704 (Figure 7). We split the solutions based on stellar mass and publish the favored set of stellar and planetary parameters in Tables 2 and 3, respectively.
4. We conducted three investigations of companions to Kepler-1704 b (Section 4.2). Firstly, an injection-recovery analysis demonstrated that the RVs of Kepler-1704 are sensitive enough to have detected planetary companions within the orbit of Kepler-1704 b down to $\sim 100 M_{\oplus}$ and companions out to a few au with a few Jupiter masses (Figure 9). Secondly, we synthesized RV time series to determine the region of mass–semimajor-axis parameter space that is consistent with

the subtle acceleration of Kepler-1704. Although this analysis does not conclusively rule out any portion of companion parameter space, it identifies a preference for those with separations greater than ~ 30 au (Figure 10, right panel). Thirdly, we conducted a dynamical simulation using the MEGNO chaos indicator that failed to substantially rule out any other regions of parameter space for additional companions (Figure 11). Based on these three analyses, we disfavor, although fail to entirely rule out, Kozai migration and secular chaos as the primary scenario to explain the orbital properties of Kepler-1704 b.

5. Using the mass and radius of Kepler-1704 b and the bimodal age of Kepler-1704, we retrieved the bulk heavy element mass and metal enrichment relative to stellar for Kepler-1704 b (Figure 12). This planet likely contains $\sim 150 M_{\oplus}$ of heavy elements, making it enriched relative to Kepler-1704 by a factor of ~ 5 . These findings suggest that Kepler-1704 b is consistent with the mass–metallicity trends of [Thorngren et al. \(2016\)](#) and theories of core accretion with late-stage heavy element accretion (Figure 13). Kepler-1704 b could have also acquired its heavy elements through core mergers during the gas accretion phase ([Ginzburg & Chiang 2020](#)).
6. Based on the aforementioned analyses, we hypothesized that Kepler-1704 b is a failed hot Jupiter (e.g., [Dawson et al. 2014](#)) that reached its high eccentricity through planet–planet scattering events, but its periastron distance was too large for efficient tidal circularization (Section 5.1). We speculated that it may have ejected companions through these events. Furthermore, based on the stellar metallicity of Kepler-1704 and the bulk composition of Kepler-1704 b, the same processes that excited this planet’s eccentricity may have also contributed to its heavy element accretion.
7. A critical missing piece of the discussion on the migration of Kepler-1704 b is the stellar obliquity (Section 5.2). Given the 5750 K effective temperature of Kepler-1704, this system can provide a valuable test of the theory that hot Jupiters preferentially align the spins of cool stars (e.g., [Winn et al. 2010](#)). A detection of the RM effect for this system is feasible, however the timing of the future transits of Kepler-1704 b (Table 4) will make this a challenging endeavour.
8. Finally, we consider prospects for characterizing the atmosphere of Kepler-1704 b (Section 4.4.1). While the large stellar radius and high planet mass may impede transmission spectroscopy, the IR phase curve

of Kepler-1704 b near periastron is expected to be detectable from *JWST* (Figure 15). Such a detection would reveal the heat redistribution properties of this cold ($T_{\text{eq}} = 254$ K, assuming no albedo) Jovian planet. Furthermore, since tidal forces are inefficient, the rotation of Kepler-1704 b is likely not pseudo-synchronized with its orbit, and its rotation period is possibly measurable via a “ringing” in thermal phase curve (e.g., [Cowan & Agol 2011b](#)).

The GOT ‘EM survey aims to characterize systems of long-period transiting giant planets, which serve as stepping stones between many exoplanet systems and the solar system ([Dalba et al. 2021a](#)). Kepler-1704 b is an extraordinary system owing to its high eccentricity and transiting geometry. Much like HD 80606 b, Kepler-1704 b provides a laboratory for testing the extremes of planetary migration scenarios. Continued observation and characterization of this system stands to refine the theories underlying the formation and evolution of all planetary systems.

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Facilities: Keck:I (HIRES), Keck:II (NIRC2), Kepler, Hale (PHARO)

Software: `astropy` (Astropy Collaboration et al. 2013, 2018), `corner` (Foreman-Mackey 2016), `EXOFASTv2` (Eastman et al. 2013; Eastman 2017; Eastman et al. 2019), `lightkurve` (Lightkurve Collaboration et al. 2018), `SpecMatch` (Petigura 2015; Petigura et al. 2017), `SpecMatch–Emp` (Yee et al. 2017), `exoplanet` (Foreman-Mackey et al. 2020), `pymc3` (Salvatier et al. 2016), `theano` (Theano Development Team 2016), `REBOUND` (Rein & Liu 2012), `RVSearch` (Rosenthal et al. 2021)

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