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HD 202772A b: A TRANSITING HOT JUPITER AROUND A BRIGHT, MILDLY EVOLVED STAR IN A VISUAL BINARY DISCOVERED BY TESS

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We report the first confirmation of a hot Jupiter discovered by the Transiting Exoplanet Survey Satellite (TESS) mission: HD 202772A b. The transit signal was detected in the data from TESS Sector 1, and was confirmed to be of planetary origin through radial velocity (RV) measurements. HD 202772A b is orbiting a mildly evolved star with a period of 3.3 days. With an apparent magnitude of $V = 8.3$, the star is among the brightest known to host a hot Jupiter. Based on the 27 days of TESS photometry, and RV data from the CHIRON and HARPS spectrographs, the planet has a mass of $1.008^{+0.074}_{-0.079} M_J$ and radius of $1.562^{+0.053}_{-0.060} R_J$, making it an inflated gas giant. HD 202772A b is a rare example of a transiting hot Jupiter around a quickly evolving star. It is also one of the most strongly irradiated hot Jupiters currently known.

*Keywords*: planetary systems, planets and satellites: detection, stars: individual (TIC 290131778, TOI 123, HD 202772)
1. INTRODUCTION

Hot Jupiters, owing to their ease of detectability, are the best-studied population of extrasolar planets. However, we still do not understand how these behemoths came into existence. Did they form in situ (Bodenheimer et al. 2000; Batygin et al. 2016), or did they arise in wider orbits and migrate to their current locations (Lin et al. 1996)? If hot Jupiters did undergo migration, was this process violent (Wu et al. 2007; Rasio & Ford 1996; Wu & Lithwick 2011; Petrovich 2015) or quiescent (Lin et al. 1996)? Are the highly inclined and eccentric orbits of some hot Jupiters a consequence of high-eccentricity migration (Winn et al. 2010; Bonomo et al. 2017), or other mechanisms that are unrelated to planet migration (Lai 2016; Duffell & Chiang 2015)? What is the occurrence rate of hot Jupiters as a function of stellar age (Donati et al. 2016)? What is the meaning of the high rate of distant companions (Knutson et al. 2014) and the low rate of close-in companions (Becker et al. 2015) to hot Jupiters? What are the connections between hot Jupiters and warm Jupiters (Huang et al. 2016), hot Neptunes (Dong et al. 2018), compact multiple-planet systems (Lee & Chiang 2016), and ultra-short-period planets (Winn et al. 2018)? Answers to these questions may come more easily if we enlarge the sample of hot Jupiters around very bright stars, subject to a wide range of irradiation levels.

The recently commissioned Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) mission has the main goal of discovering transiting exoplanets around bright and nearby stars, thereby facilitating follow-up studies. A few dozen hot Jupiters orbiting bright ($V \lesssim 10$ mag) stars are expected to emerge from the TESS mission (Sullivan et al. 2015; Barclay et al. 2018; Huang et al. 2018). They will always be among the most observationally favorable transiting planets, and as such, they will observed and re-observed in perpetuity as astronomical capabilities advance.

Here we report the first confirmation of a hot Jupiter discovered by the TESS mission, HD 202772A b. Sec. 2 presents the data. Sec. 3 describes the derivation of the host star characteristics, and Sec. 4 presents the system parameters based on fitting the available photometry and RV data. Sec. 5 summarizes the results and places this discovery into context.

2. OBSERVATION AND DATA REDUCTION

2.1. TESS Photometry

HD 202772 (TIC 290131778, TOI 123) was observed by Camera 1 of the TESS spacecraft during the first sector of science operations, between 2018 July 25 and 2018 August 22 (BJD 2458325 to 2458353). The available data have two-minute time sampling (“short cadence”). Some basic parameters of the target are given in Table 1. Given its position in the sky, HD 202772 will not be re-observed during the TESS primary mission. The photometric data were analyzed by the Science Processing Operations Center (SPOC) pipeline, based on the NASA Kepler mission pipeline (Jenkins et al., in prep). The light curve of HD 202772 presented in Fig. 1 shows a clear transit signal. It was listed among the TESS Alerts published online on 2018 September 5, prompting us to download the photometric time series.

We detrended the raw light curves in the following way (see e.g. Günther et al. 2017, 2018). After masking out all of the data obtained during transits, we fitted a Gaussian Process (GP) model to the data, using a Matern 3/2 kernel and a white noise kernel. For this task we employed the Celerite package, which uses a Taylor-series expansion of these kernel functions. Once the parameters of the GP were constrained based on the out-of-transit data, we used it to detrend the entire light curve.

The SPOC pipeline produces flags for poor-quality exposures. These include exposures taken during the 30-minute long momentum dumps that occurred every 2.5 days (10 times in total). All flagged exposures were...
2.2. Keck/NIRC2 Adaptive Optics Imaging

HD 202772 was reported to be a pair of stars in several wide-field surveys (e.g. Tycho-2, Hog et al. 2000; PP-MXL, Roeser et al. 2010; Gaia DR2, Gaia Collaboration et al. 2018; see also Holden 1978, Horch et al. 2001) reported two bright stars separated by ≈1.5", although the Gaia DR 2 catalog flags the brighter star as a “duplicate” entry. To check on these earlier findings, we performed high-resolution adaptive optics (AO) imaging at Keck Observatory.

The Keck observations were made with the NIRC2 instrument on Keck-II behind the natural guide star AO system. The observations were made on 2018 September 18 on a night with partial cirrus conditions. We used the standard 3-point dither pattern that avoids the left lower quadrant of the detector (which is typically noisier than the other three quadrants). The dither pattern step size was 3", and it was repeated twice, with the second dither offset from the first dither by 0.5". Observations were made with three different filters: narrow-band Brγ (λ0 = 2.1686; Δλ = 0.0326 μm), H-continuum (λ0 = 1.5804; Δλ = 0.0232 μm), and J-continuum (λ0 = 1.2132; Δλ = 0.0198 μm), using inte-
The bright-ness of each injected source was scaled until standard aperture photometry detected it with 5σ significance. The resulting brightness of the injected sources relative to our target was taken to be the contrast limit for the injected location. The final 5σ limit at each separation was determined from the average of all of the determined limits at that separation, with an uncertainty given by the RMS dispersion of the results for different azimuthal slices. Figure 2 shows the 2 μm sensitivity curve in black, with the 1σ (RMS) dispersion marked in purple. The inset image shows the primary target in the center and the second source located 1.3″ to the northwest.

The two stars were detected in all three filters. The presence of the blended companion must be taken into account to obtain the correct transit depth and planetary radius (Ciardi et al. 2015). The stars have blended 2MASS magnitudes of \( J = 7.232 \pm 0.026 \) mag, \( H = 7.048 \pm 0.021 \) mag, and \( K_s = 6.945 \pm 0.026 \) mag. The stars have measured magnitude differences of \( \Delta J = 1.705 \pm 0.0015 \) mag, \( \Delta H = 1.631 \pm 0.008 \) mag, and \( \Delta K_s = 1.709 \pm 0.011 \) mag. The primary star has de-

Based on the TESS magnitude and 2MASS color relationships established for the TESS Input Catalog (Stassun et al. 2018), we estimate that the deblended TESS magnitudes for the two components to be \( T_1 = 7.92 \pm 0.09 \) mag and \( T_2 = 9.62 \pm 0.09 \) mag for a TESS magnitude difference of \( \Delta T = 1.7 \pm 0.1 \) mag and a TESS flux ratio of \( F_2/F_1 = 0.21 \pm 0.02 \). We used this value of the flux ratio to correct the apparent transit depth in the TESS light curve, and derive the unblended transit depth.

We will refer to the brighter target (hosting the planet) as HD 202772A, and the fainter companion as HD 202772B. Given the similarity between the two stars, and a projected separation of only \( \sim 200 \) AU, it seems very likely that the two stars are gravitationally bound. The chance alignment probability is negligible, as estimated from the Besançon Galactic Model (Robin et al. 2003). We have also checked all 131 stars in the Gaia DR2 catalog within 300″ of HD 202772A with measured parallax and proper motion, and the only nearby source with a similar projected velocity is HD 202772B.

2.3. LCO/NRES Optical Spectroscopy

To obtain independent estimates of the stellar parameters, we performed high-resolution optical spectroscopy with the Las Cumbres Observatory (LCO) robotic network of telescopes (Brown et al. 2013). We obtained three 20-minute exposures with a total signal-to-noise ratio (SNR) \( \approx 100 \) with the Network of Echelle Spectrographs (NRES; Siverd et al. 2016, 2018) mounted on a 1.0m telescope at the South African Astronomical Observatory (SAAO).

Since the NRES fiber diameter corresponds to 2.8″, it captured the light from both stars in the visual binary system. Using TODCOR (Zucker & Mazeh 1994), we identified two RV components separated by \( 5 \pm 1 \) km s\(^{-1}\). This RV difference is compatible with the order of magnitude of the RV variation one would expect from the

**Figure 2.** AO image (inset) and \( K_s \)-band contrast curves for HD 202772A, obtained with Keck/NIRC2. A companion is visible 1.3″ northwest of the primary. The black line is the 5σ sensitivity, with a 1σ scatter marked in purple. See text for further details.
orbital motion of the stars, given their masses and sky-projected separation.

2.4. Keck/HIRES Optical Spectroscopy

In order to obtain a spectrum of each of the two stars with minimal contamination from the other star, we observed both stars with Keck/HIRES (Vogt et al. 1994) on 2018 September 23. We obtained one spectrum of each star, with the HIRES slit oriented perpendicular to the separation between the two stars. Given the angular separation between the two stars, the slit width (0.86″) and the astronomical seeing at Keck at the night of the observation (∼0.7″), the level of cross-contamination is expected to be less than 10%. Both spectra were obtained without the iodine (I$_2$) cell, at a spectroscopic resolution of R≈65,000, and at a signal-to-noise ratio per pixel of 150 at 5500 Å. A similar technique was successfully applied by Shporer et al. (2014) to a visual binary system in which both members have similar brightness and a smaller angular separation.

2.5. Doppler Velocimetry with CHIRON

We obtained a total of 14 spectra of HD 202772A using CHIRON (Tokovinin et al. 2013), a fiber-fed high-resolution optical spectrograph mounted on the SMARTS 1.5m telescope at Cerro Tololo in Chile. We collected the spectra using the image slicer, which delivers a resolution of ∼80,000 and a higher throughput than the standard slit mode. Our 15-minute exposures yielded a SNR per pixel of ∼60-80 at 5500 Å.

Although CHIRON is equipped with an iodine cell to obtain a precise wavelength solution that permits long-term RV precision better than ∼2-3 m s$^{-1}$ (e.g. Jones et al. 2017), we did not use the iodine cell for these observations. This is because the cell absorbs ∼25% of the light at 5500Å, significantly decreasing the signal-to-noise ratio. Moreover, using the I$_2$ cell requires a time-consuming acquisition of a high-SNR template spectrum of the target star.

Instead, we derived the RVs using the Cross-Correlation-Function (CCF) method, in a manner similar to Jones et al. (2017). CHIRON is not equipped with a simultaneous calibration fiber. Instead, we acquired a Th-Ar lamp exposure before and after each target exposure. We computed the wavelength solution for the target spectra by interpolating line positions for the lamps to match the temporal midpoint of each observation. We thereby achieved a RV stability of ∼5-6 m s$^{-1}$, which was verified with two RV standard stars observed nightly. The resulting RVs of HD 202772A are listed in Table 3. RVs collected by CHIRON show a ∼95 m s$^{-1}$ sinusoidal variation in phase with the transit ephemeris.

Finally, from the CCF, we measured the bisector velocity span (BVS) and FWHM variations, to check on the possibility that the observed RV variation results from stellar activity or a background eclipsing binary system (see, e.g., Santerne et al. 2015). Fig. 6 shows the BVS and FWHM as a function of the measured radial velocities. There is no significant correlation between these quantities and the radial velocities.

The CHIRON fiber has a 2.7″ diameter on the sky, but HD 202772A and B are separated by only 1.3″, which means that we must expect some of the light from the other star to contaminate the spectrum.
2.6. Doppler Velocimetry with FLWO 1.5m/TRES

We obtained 12 spectra of HD 202772A with the Tillinghast Reflector Echelle Spectrograph (TRES; Fűrész 2008) on the 1.5m Tillinghast Reflector at Fred L. Whipple Observatory (FLWO) on Mt. Hopkins, AZ between UT 2018 September 14 and UT 2018 September 30. TRES is a fiber-fed, cross-dispersed echelle spectrograph with a resolving power of $R \sim 44,000$ and an instrumental precision of $\sim 10–15$ m s$^{-1}$. The typical exposure time was $\sim 4$ minutes, resulting in SNR per resolution element of $\sim 75$ at 5200Å. The spectra are calibrated using a ThAr lamp, exposed through the science fiber before and after each set of science exposures. We note that the TRES fiber is 2.3″, and the exposures therefore include light from HD 202772B.

We reduced and analyzed the spectra according to the procedures outlined in Buchhave et al. (2010). Namely, the spectra were optimally extracted and then cross-correlated, order by order, against the strongest spectrum of HD 202772A. We exclude spectral orders far to the blue where the SNR is low, in the red where telluric lines contaminate the spectrum, and a few orders in between with little information content or affected by broad feature (e.g., Balmer lines) toward the edge of the order that affect continuum fitting. RVs were ultimately derived from a region spanning 4130–6280Å. The peak of the summed CCF across all orders is fit to derive the final RV, and the scatter between orders within a each spectrum is taken to be the internal error estimate. These relative RVs and their uncertainties are reported in Table 3.

We also derive the BVS and FWHM from the cross-correlation function of each spectrum against a non-rotating synthetic spectrum with appropriate $T_{\text{eff}}$, $\log g$, and [Fe/H]. These values are also reported in Table 3 and shown in Figure 6, and show no correlation with the RVs.

2.7. Doppler Velocimetry with HARPS

To provide further confirmation of the planetary origin of the transit signal, we obtained 9 spectra using the High Accuracy Radial velocity Planet Searcher (HARPS; Mayor et al. 2003). These data were obtained during three consecutive nights in good seeing conditions ($\lesssim 1.0″$). Exposure time was 200-300 seconds, leading to a SNR of $\sim 70–80$ at 6,000 Å. We carefully centered the brighter star within the 1″ aperture fiber, to ensure that no light contamination from the companion was reaching the detector. We also carefully adjusted the size of the guiding box, to avoid guiding problems due to the secondary star, which was clearly visible in the acquisition camera. During the HARPS observations, the Moon was between 13° and 36° from our target, with an illuminated fraction between 92% and 99%. This led to some lunar contamination in the spectra. Moreover,
the RV of the Moon was very close to the RV of the target star, which severely affected the shape of the CCF. For this reason, we discarded the two RV data points that were most affected and had very deviant values. Also, due to the contamination, the derived BVS and FWHM of the CCF are not reliable, and are not listed in Table 3. We processed the HARPS data using the CERES code (Brahm et al. 2017). The resulting RVs are listed in Table 3, and also shown in Figure 4. As can be seen, the HARPS data agree with the CHIRON data, although the scatter around the fit is larger than expected. This is most likely caused by the lunar light contamination.

3. STELLAR PARAMETERS

3.1. Results from CHIRON

To derive the stellar atmospheric parameters of HD 202772A we measured the equivalent widths (EWs) of about 150 relatively weak Fe i and Fe ii absorption lines (EW \(\lesssim 120\) m\(\AA\)). The EWs were measured in the high-SNR template obtained by stacking the individual spectra (see Sec. 2.5), using the ARES v2 automatic tool (Sousa et al. 2015).

We then used the MOOG code (Sneden 1973) along with the Kurucz (1993) stellar atmosphere models to solve the radiative transfer equations under the assumptions of local excitation and ionization equilibrium via the Saha and Boltzmann equations. For each iron line, MOOG computes the corresponding iron abundance by matching the measured EW in the curve of growth computed from the input stellar model. This procedure is performed iteratively for models with different effective temperatures (\(T_{\text{eff}}\)), iron abundances ([Fe/H]), and micro-turbulent velocities (\(V_{\text{micro}}\)) until there is no correlation between the line excitation potential and wavelength with the model abundance. Finally, we obtained the surface gravity (\(\log g_\star\)) using the constraint that the iron abundances derived from both the Fe i and Fe ii lines should be the same (For a more thorough description of the procedure, see Jones et al. 2011). Table 2 gives the resulting stellar parameters.

We computed the luminosity of HD 202772A based on the Gaia DR2 parallax (\(\pi = 6.166 \pm 0.092\), Gaia Collaboration et al. 2018), the apparent \(V\) magnitude (after correcting for interstellar absorption by \(A_V = 0.10\) mag), and the bolometric correction of (Alonso et al. 1999). Using this information and the stellar atmospheric parameters (\(T_{\text{eff}}\) and [Fe/H]), we derived the stellar physical parameters using the PARSEC stellar-evolutionary models (Bressan et al. 2012). The results are also listed in Table 2.

3.2. Results from FLWO 1.5m/TRES

We used the Spectral Parameter Classification (SPC) tool (Buchhave et al. 2012) to derive stellar parameters from the TRES spectra. We allowed \(T_{\text{eff}}\), \(\log g_\star\), [Fe/H], and \(V \sin i\) to be free parameters. SPC works by cross correlating an observed spectrum against a grid of synthetic spectra based on Kurucz atmospheric models (Kurucz 1993). The weighted average results are listed in Table 2.

3.3. Results from LCO/NRES

We analyzed the LCO/NRES spectrum using the methodology of Fulton & Petigura (2018). We measured \(T_{\text{eff}}\), \(\log g_\star\), [Fe/H], and \(V \sin i\) using SpecMatch (Petigura 2015)\(^2\), which compares the observed spectrum with a grid of model spectra (Coelho et al. 2005). The resulting parameters are listed in Table 2.

To calculate the star’s physical parameters, we used isoclassify (Huber et al. 2017), which takes as input the effective temperature, metallicity, parallax, and apparent \(K_\star\) magnitude. Using the isoclassify “direct” mode, we calculated the posterior probability distributions for \(R_\star\) and \(L_\star\) by applying the Stefan–Boltzmann law. Using the isoclassify “grid” mode, we calculated the range of MIST isochrone models (Dotter 2016; Choi et al. 2016) that are consistent with the spectroscopic parameters to estimate the stellar mass and age. The results of the SpecMatch+isoclassify analysis are listed in Table 2.

3.4. Results from Keck/HIRES

The Keck/HIRES spectrum of each of the two stars was also analyzed using SpecMatch. The resulting atmospheric and physical stellar parameters for both HD 202772A and B are listed in Table 1 and Table 2. The stellar parameters derived from resolved HIRES spectra show good agreement with those from the CHIRON, TRES, and NRES spectra, except that TRES finds modestly lower [Fe/H]. Evidently, the contaminating light from the secondary star in the CHIRON, TRES, and NRES spectra did not strongly affect the determination of the basic stellar parameters.

4. PLANETARY SYSTEM PARAMETERS FROM GLOBAL ANALYSIS

We performed a joint analysis of the TESS data, the RV data, and the stellar spectral energy distribution using EXOFASTv2\(^3\) (Eastman et al. 2013, 2017).

\(^2\) https://github.com/petigura/specmatch-syn
\(^3\) https://github.com/jdeast/EXOFASTv2
Figure 7. The position of HD 202772A b (red) in the space of mass, radius, and irradiation, compared to the population of known transiting gas giant planets (black). In the left panel, the solid lines mark theoretical models taken from Baraffe et al. (2014) for no core (black) and a 100 M_{Earth} core (gray). The dashed lines are isodensity contours. Data were obtained from the NASA Exoplanet Archive (Akeson et al. 2013) on 2018 September 15.

The stellar limb darkening function was assumed to be quadratic, with the coefficients fit with a prior from Claret (2018) for the TESS band based on the log g*, T_{eff}, and [Fe/H] at each step. We imposed Gaussian priors on the Gaia DR2 parallax of 6.77 ± 0.11 mas (after adjusting by 82 μas as advocated by Stassun et al. 2018) and the TESS-band dilution from the neighboring star of 0.21 ± 0.02 found from the AO imaging. We imposed an upper limit on the V-band extinction of 0.17236 from Schlafly & Finkbeiner (2011). The priors for all the remaining parameters were uniform and unbounded.

To constrain the spectral energy distribution, we use the broadband photometry from Tycho (which resolved the companion), and the 2MASS JHK photometry after deblending based on the Keck AO images. We opted not to impose any informative priors on the spectroscopic parameters T_{eff} or [Fe/H]. Instead, we relied on the observed spectral energy distribution and the MIST stellar-evolutionary models to constrain the stellar parameters. The resulting stellar parameters are listed in Table 2, and show good agreement with the results of the spectroscopic analysis. Table 4 gives the results of the EXOFAST fit to all of the data. The best-fitting model is also plotted in Figures 3, 4, and 5.

5. DISCUSSION

HD 202772A b is an inflated Jupiter-mass planet orbiting a metal-rich star with an orbital period of 3.3 days. The red dots in Fig. 7 show the location of this newly discovered planet in the spaces of planetary mass, radius, and incident flux, compared with the current sample of transiting giant planets. HD 202772A b is one of the largest known planets, with a relatively low mean density of 0.33 g cm^{-3}. It is also one of the most strongly irradiated planets, thereby obeying the well known correlation between planetary radius and degree of irradiation (see, e.g., Laughlin et al. 2011; Lopez & Fortney 2016). Based on the irradiation of 4.7×10^{9} erg s^{-1} cm^{-2}, the estimated equilibrium temperature is about 2,100 K (see Table 4).

The large size of HD 202772A b might be connected to the evolutionary state of the host star (Grunblatt et al. 2017). Fig. 8 shows the location of HD 202772A in the space of surface gravity and effective temperature. HD 202772A is slightly evolved, with a relatively low surface gravity. As a star evolves, its luminosity increases, which also increases the flux of radiation impinging on any planets. If giant planets are “inflated” by intense stellar radiation, as has long been proposed, then the larger-than-usual size of HD 202772A b suggests that the evolutionary timescale of the star is slower than the inflationary timescale of the planet.

HD 202772A will exhaust its hydrogen fuel in ∼0.5 Gyrs, which may have ramifications for the survival of the planet. The apparent paucity of hot Jupiters orbiting evolved stars (Johnson et al. 2007) has been interpreted as a consequence of tidal destruction (Villaver & Livio 2009; Schlaufman & Winn 2013). Tides raised on the star by the planet cause the planet to transfer angular momentum to the star, a process that is thought to accelerate rapidly as the star grows in size. However, the timescale for this process is unknown, with an uncertainty spanning several orders of magnitude.

The recent discoveries of close-in gas giants around subgiants (e.g. Van Eylen et al. 2016), or even red giants (e.g. Jones et al. 2018) suggest that the lifetimes of hot Jupiters in those systems may not as short as we
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$^1$The HARPS BVS and FWHM are not listed because those measurements were corrupted by moonlight (Section 2.7).

Figure 8. Surface gravity and effective temperature of the hosts of transiting giant planets (similar to an H-R diagram). The position of HD 202772A (red) falls near the edge of the occupied region of parameter space. The solid gray line is the best-fitting MIST stellar mass track. Data were obtained from the NASA Exoplanet Archive (Akeson et al. 2013) on 2018 September 15.

thought. Alternatively, as predicted by Stephan et al. (2018), the eccentric Kozai-Lidov mechanism in a binary stellar system can drive a longer period Jupiter migrate inward during the post-main sequence phase. It seems that with the distant stellar companion, HD 202772A b is consistent with this scenario. A likely prediction from this scenario is that HD 202772A b may have a non zero stellar obliquity (the angle between the orbital axis and the stellar spin axis), which can be tested in future observations. From the stellar and planetary parameters we obtained, we predict that the Rossiter-McLaughlin effect with have an RV semi-amplitude of 10.5 m s$^{-1}$ (e.g., Winn et al. 2005; Gaudi & Winn 2007; Albrecht et al. 2012; Wang et al. 2018).

However, it is impossible to draw any firm conclusions until we can measure the occurrence rates of such planets using a homogenous data set. The TESS survey should eventually provide the opportunity to perform such a study, by detecting thousands of new planets orbiting a wider variety of stars than were observed in the Kepler mission.

We thank Yanqin Wu, Smadar Naoz, Lars A. Buchhave, Bonan Pu, Alexander P. Stephan, Sabarni Basu, Beibei Liu, and Jorge Lillo-Box for their insights. J.N.W. and S.W. thanks the Heising-Simons Foundation for their generous support. M.N.G. acknowledges support from MIT’s Kavli Institute as a Torres post-doctoral fellow. S.M. and A.B.D. are supported by the National Science Foundation Graduate Research Fellowship Program under Grant Number DGE-1122492. R.B. acknowledges support from FONDECYT Post-doctoral Fellowship Project 3180246, and from the Millennium Institute of Astrophysics (MAS). This research is based on observations collected at the European Organization for Astronomical Research in the Southern Hemisphere under ESO programme 0101.C-0232. This work makes use of observations from SMARTS and the LCO network. We acknowledge the use of TESS Alert data, which is currently in a beta test phase, from the TESS Science Office and the TESS Science Processing Operations Center. Funding for the TESS
mission is provided by NASA’s Science Mission directorate. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. This research has made use of the Exoplanet Follow-up Observation Program website, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. We made use of the Python programming language (Rossum et al. 1995) and the open-source Python packages NUMPY (van der Walt et al. 2011), EMCEE (Foreman-Mackey et al. 2013), and CELERITE (Foreman-Mackey et al. 2017).

Facilities:

Facility: TESS,
Facility: CTIO:1.5m (CHIRON),
Facility: ESO:3.6m (HARPS),
Facility: Keck II (NIRC2),
Facility: Keck I (HIRES),
Facility: LCO:1.0m (NRES),
Facility: FLWO:1.5m (TRES)
Table 4. Median values and 68% confidence interval for HD 20772A planetary system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>Values</th>
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<tr>
<td><strong>Stellar Parameters:</strong></td>
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<tr>
<td>$M_\star$</td>
<td>Mass ($M_\odot$)</td>
<td>$1.703^{+0.075}_{-0.12}$</td>
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<tr>
<td>$R_\star$</td>
<td>Radius ($R_\odot$)</td>
<td>$2.614^{+0.080}_{-0.11}$</td>
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<tr>
<td>$L_\star$</td>
<td>Luminosity ($L_\odot$)</td>
<td>$9.25^{+0.58}_{-0.60}$</td>
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<tr>
<td>$\rho_\star$</td>
<td>Density (cgs)</td>
<td>$0.134^{+0.014}_{-0.015}$</td>
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<tr>
<td>$\log g_\star$</td>
<td>Surface gravity (cgs)</td>
<td>$3.835 \pm 0.034$</td>
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<tr>
<td>$T_{\text{eff}}$</td>
<td>Effective Temperature (K)</td>
<td>$6230^{+110}_{-98}$</td>
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<tr>
<td>$[\text{Fe/H}]$</td>
<td>Metallicity (dex)</td>
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<tr>
<td>$\sigma_{\text{SED}}$</td>
<td>SED photometry error scaling</td>
<td>$3.6^{+3.8}_{-1.5}$</td>
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<tr>
<td>$\pi$</td>
<td>Parallax (mas)</td>
<td>$6.79 \pm 0.11$</td>
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<tr>
<td>$d$</td>
<td>Distance (pc)</td>
<td>$147.2^{+2.4}_{-5.7}$</td>
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</table>

| **Period (days)** | $3.308960 \pm 0.000082$ |
| **Radius ($R_\odot$)** | $1.564^{+0.053}_{-0.069}$ |
| **Time of conjunction (BJD$_{\text{TDB}}$)** | $2458328.68358 \pm 0.00035$ |
| **Optimal conjunction Time (BJD$_{\text{TDB}}$)** | $2458338.61046 \pm 0.00024$ |
| **Semi-major axis (AU)** | $0.05196^{+0.00075}_{-0.00072}$ |
| **Inclination (Degrees)** | $84.20^{+1.1}_{-0.46}$ |
| **Eccentricity** | $0.047^{+0.050}_{-0.033}$ |
| **Argument of Periastron (Degrees)** | $88^{+3.4}_{-1.20}$ |
| **Equilibrium temperature ($^\circ$C)** | $213^{2.37}_{+1.33}$ |
| **Mass ($M_\odot$)** | $1.008^{+0.0074}_{-0.0079}$ |
| **RV semi-amplitude (m/s)** | $96.9^{+1.0}_{-0.8}$ |
| **Log of RV semi-amplitude** | $1.986^{+0.028}_{-0.028}$ |
| **Radius of planet in stellar radii** | $0.0614^{+0.00003}_{-0.00008}$ |
| **Semi-major axis in stellar radii** | $4.27^{+0.17}_{-0.15}$ |
| **Transit depth (fraction)** | $0.00377^{+0.00003}_{-0.00009}$ |
| **Decrement at mid transit** | $0.00377^{+0.00001}_{-0.00009}$ |
| **Ingress/egress transit duration (days)** | $0.0165 \pm 0.0011$ |
| **Total transit duration (days)** | $0.234^{+0.0001}_{-0.0012}$ |
| **FWHM transit duration (days)** | $0.2179^{+0.00062}_{-0.00058}$ |
| **Transit Impact parameter** | $0.416^{+0.055}_{-0.078}$ |
| **Density (cgs)** | $0.339^{+0.046}_{-0.036}$ |
| **Surface gravity** | $3.012^{+0.041}_{-0.039}$ |
| **Incident Flux ($10^9$ erg s$^{-1}$ cm$^{-2}$)** | $4.68^{+0.32}_{-0.28}$ |
| **Time of Periastron (BJD$_{\text{TDB}}$)** | $2458328.74^{+0.49}_{-0.35}$ |
| **Time of eclipse (BJD$_{\text{TDB}}$)** | $2458330.33^{+0.043}_{-0.051}$ |
| **Minimum mass ($M_\odot$)** | $1.002^{+0.074}_{-0.079}$ |
| **Mass ratio** | $0.00057^{+0.000042}_{-0.000037}$ |
| **Separation at mid transit** | $4.12^{+0.30}_{-0.36}$ |

Table 4 continued
### Table 4 (continued)

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<tr>
<th>Parameter</th>
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<td>$\sigma_J$</td>
<td>RV Jitter (m/s)</td>
<td>$14.8^{+5.5}_{-1.1}$</td>
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1 Assuming zero albedo and full heat distribution from day to night hemispheres.

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