The Magellan/PFS Exoplanet Search: A 55-day period dense Neptune transiting the bright \((V = 8.6)\) star HD 95338†‡

Matías R. Díaz,1,* James S. Jenkins,1 Fabo Feng,2 R. Paul Butler,2 Mikko Tuomi,3 Stephen A. Shectman,4 Daniel Thorngren,5,6 Maritza G. Soto,7 José I. Vines,1 Johanna K. Teske,4,11 Diana Dragomir,8 Steven Villanueva,9 Stephen R. Kane,10 Zaira M. Berdiñas,1 Jeffrey D. Crane,4 Sharon X. Wang,2,4 Pamela Arriagada2

1 Departamento de Astronomía, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
2 Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5124 Broad Branch Road, Washington, DC 20015-1305, USA
3 Center for Astrophysics Research, School of Physics, Astronomy and Mathematics, University of Hertfordshire, College Lane, Hatfield AL109AB, UK
4 The Observatories, Carnegie Institution for Science, 813 Santa Barbara Street, Pasadena, CA 91101, USA
5 Department of Physics, University of California, Santa Cruz, USA
6 Institut de Recherche sur les Exoplanètes, Université de Montréal, Canada
7 School of Physics and Astronomy, Queen Mary University of London, G.O. Jones Building, 327 Mile End Road London, E1 4NS, UK
8 Department of Physics and Astronomy, University of New Mexico, 1919 Lomas Blvd NE, Albuquerque, NM 87131, USA
9 MIT Kavli Institute for Astrophysics & Space Research, 77 Massachusetts Ave. Building 37-582 BB, Cambridge, MA 02139, USA
10 Department of Earth and Planetary Sciences, University of California Riverside, 900 University Ave., Riverside, CA 92521, USA
11 NASA Hubble Fellow

† This paper includes data gathered with the 6.5 m Magellan Telescopes located at Las Campanas Observatory, Chile.
‡ Additional observations were acquired with the ESO-3.6m telescope at La Silla Observatory under programs 0101.C-0497, 0102.C-0525 and 0103.C-0442.
* corresponding author, matias.diaz.m@ug.uchile.cl

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We report the detection of a transiting, dense Neptune planet candidate orbiting the bright \((V = 8.6)\) K0.5V star HD 95338. Detection of the 55-day periodic signal comes from the analysis of precision radial velocities from the Planet Finder Spectrograph on the Magellan II Telescope. Follow-up observations with HARPS also confirm the presence of the periodic signal in the combined data. HD 95338 was also observed by the Transiting Exoplanet Survey Satellite (TESS), and we identify a clear single transit at the period corresponding to the signal detected in the radial velocity data. A Markov Chain Monte Carlo period search on the velocities allows strong constraints on the expected transit time, matching well the epoch calculated using TESS. A joint fit model yields an absolute mass of \(39.43^{+6.04}_{-4.13} M_{\oplus}\) and a radius of \(3.98^{+0.09}_{-0.08} R_{\oplus}\) which translates to a density of \(3.41^{+0.56}_{-0.40} g \text{ cm}^{-3}\) for the planet. Given the planet mass and radius, structure models suggest it is fully composed of ice. HD 95338b is one of the most dense Neptune planets yet detected, indicating a heavy element enrichment of \(\sim 90\% (\sim 35 M_{\oplus})\). This system presents a unique opportunity for future follow-up observations that can further constrain structure models of cool gas giant planets.

Key words: Planetary Systems – techniques: radial velocities, photometric – planets and satellites: fundamental parameters, detection

1 INTRODUCTION

As the transit probability of a planet orbiting a star decreases with increasing orbital period, or star-planet separation, the majority of transiting systems contain planets with orbital periods of less than 10 days. For planets with longer periods, not only does the probability decrease compared with the shorter period counterparts, but they are also much more difficult to detect and confirm logistically, using ground-based transit surveys. Large-scale surveys have been setup to try to target longer period transiting systems (e.g., HATSouth, Bakos et al. 2013; NGTS, Wheatley et al. 2017), but they are generally limited to detection sensitivities that fall off after 12 days, due to the observing window function problem (Bakos et al. 2013). Space-based surveys can bypass this issue due to their, almost, continual monitoring capabilities.

The CoRoT (Baglin et al. 2006), Kepler (Borucki et al. 2010),
and K2 (Howell et al. 2014) space missions paved the way for the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) mission. CoRoT, and Kepler in particular, were able to provide some startling discoveries, particularly giving a first glimpse into the structural properties of small planets (e.g., CoRoT-7b, Léger et al. 2009; Kepler-10 b, Batalha et al. 2011). However, what we have learned about giant planets has mainly come from ground-based planet detections, due in no small part to the ease of radial-velocity (RV) follow-up that is a requirement to constrain the mass and density of transit detections.

Detailed studies have been possible for a handful of gas giant planets. For example, two of the most well-known planets are HD 189733 b (Bouchy et al. 2005) and HD 209458 b (Henry et al. 2000). HD 209458 b was the first confirmed transiting planet (Charbonneau et al. 2000) and was also the first that allowed us to detect elements in its escaping atmosphere, in this case Na and CO (Charbonneau et al. 2002). HD 189733 b also orbits a fairly bright star, and therefore we also found this object to have an inflated atmosphere that is in the process of being evaporated due to the close proximity of the host star (Lecavelier des Etangs et al. 2012; Bourrier et al. 2013). From its escaping atmosphere Sodium D absorption has been characterized (Salz et al. 2016). Recent studies have revealed water vapor absorption on the planet’s atmosphere (Birkby et al. 2013; Alonso-Floriano et al. 2019) and also absorption due to methane (Brogi et al. 2018). Beyond these two planets, we now have a number of transiting gas giants that have revealed their atmospheric make-up (e.g., GJ 3470 b, Nascimbeni et al. 2013; WASP-12 b, Kreidberg et al. 2015; MASCARA-2 b/KELT-20 b, Casasayas-Barris et al. 2019; KELT-9 b, Turner et al. 2020).

Although we have learned a great deal about gas giants, the vast majority of what we know applies only to the hottest subset, those closest to their stars that are heavily irradiated. The equilibrium temperatures of these hot Jupiters are generally >1000 K, and therefore their atmospheric chemistries and physical properties are very different to those on longer period orbits, like Jupiter in our solar system. The population of longer period transiting planets is growing (e.g. HATs-17 b, Brahms et al. 2016; Kepler-538 b, Mayo et al. 2019; EPIC 249893012 c & d, Hidalgo et al. 2020), particularly since the introduction of TESS that finds transits orbiting significantly brighter stars than Kepler or K2, and across the whole sky (e.g., HD 1397 b, Brahms et al. 2019; TOI-667 b, Jordán et al. 2019; HD 21740 b & c, Dragomir et al. 2019, LTT 9779 b, Jenkins et al. 2020). However, despite these Discoveries, we still know of not many known transiting planets with orbital periods greater than 40 days, orbiting stars bright enough for detailed atmospheric characterization ($V < 9$).

Here we introduce HD 95338 b, a Neptune analogue planet detected using precision RVs as part of the Planet Finder Spectrograph (PFS; Crane et al. 2006, 2008, 2010) long term planet search project, and which we found to transit after analyzing the TESS lightcurve. HD 95338 b is the first planet candidate from TESS discovered with a period larger than 27 days (the time baseline of the TESS data series). Therefore, it is the first single-transit planet detected from the TESS mission.

2 SPECTROSCOPIC OBSERVATIONS

High-precision Doppler measurements of HD 95338 were acquired using PFS mounted on the 6.5 m Magellan II (Clay) telescope at Las Campanas Observatory, and the High Accuracy Radial velocity Planet Searcher (HARPS; Pepe et al. 2002) installed on the ESO 3.6 m telescope at La Silla Observatory.

2.1 PFS

Observations were carried out using PFS between February 26 2010 and May 25 2018, as part of the Magellan Exoplanet Long Term Survey (LTS). PFS uses an iodine cell for precise RV measurements and it delivers a resolving power of $R \sim 8000$ in the iodine region when observing with the $0.3'' \times 2.5''$ slit. Iodine-free template observations were acquired with the $0.3'' \times 2.5''$ slit at a resolving power of $R \sim 127000$. 52 observations were acquired using an average of 540 s of exposure time yielding a mean radial velocity uncertainty of 1.13 m s$^{-1}$ and a median SNR~144.

PFS was upgraded with a new CCD detector in 2017. The new CCD is a 10k×10k sensor and has smaller pixels, which improves the line sampling in the spectra. In addition, regular LTS stars are now observed using the $0.3'' \times 2.5''$ slit, therefore improving the resolution. The data using this new setup is labeled as PFS2 and includes 31 observations. For this upgraded setup, the mean exposure time used was 485 s for each observation giving rise to a mean radial velocity uncertainty of 0.87 m s$^{-1}$ for a median SNR~74. The radial velocities are computed with a custom pipeline following the procedure outlined by Butler et al. (1996). They are listed in Table 1 and 2.

The spectral wavelength range in PFS covers the Ca II H & K lines, enabling the possibility of deriving S-indices to monitor the stellar chromospheric activity. S-indices are derived using the prescription outlined by Baliunas et al. (1996) and Boisse et al. (2011). In general, authors determine their S-index errors based on photon noise on the CCD (Boisse et al. 2011; Lovis et al. 2011; Jenkins et al. 2017). In our case, however, doing so can grossly underestimate the real error, reporting < 1% or smaller, as they are probably dominated by instrumental systematics (e.g., wavelength calibration, normalization errors). To avoid any bias to unrealistic error estimation we assumed a homogeneous 5% errorbar estimated from the RMS of the S-index series.

2.2 HARPS

Eleven observations using HARPS were acquired between May 24 2018 and April 6 2019 from program IDs 0101.C-0497, 0102.C-0525 and 0103.C-0442 (PI: Diaz), in order to confirm the signal found in PFS data and also to constrain the orbital parameters of the planet candidate. The observations were carried out using simultaneous Thorium exposures with a fixed exposure time of 900 s reaching a mean signal-to-noise ratio of ~67 at 5500 Å. We reprocessed the observations with the TERRA software (Anglada-Escudé & Butler 2012), where a high S/N template is constructed by combining all the observations that pass a threshold S/N cutoff, and then the RVs are computed by a χ$^2$-fitting process relative to this template. The mean radial velocity uncertainty we get from this analysis is ~0.89 m s$^{-1}$. TERRA also provides a computation of the S-indices and their uncertainties. These along with the RVs are listed in Table 3.
Table 1. PFS1 Radial Velocities of HD 95338. This table is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content.

| BJD (- 2450000) | RV (m s$^{-1}$) | $\sigma$ RV (m s$^{-1}$) | S (dex) | $\sigma$ S (dex) |
|-----------------|-----------------|-----------------|--------|----------------|
| 5253.72066      | 1.806           | 1.191           | 0.2450 | 0.012          |
| 5256.80073      | 3.796           | 1.186           | 0.1867 | 0.012          |
| 5342.53484      | -2.873          | 1.114           | 0.3596 | 0.012          |
| 5348.50146      | 0.620           | 1.317           | 0.2815 | 0.012          |
| 5349.52059      | -1.081          | 1.371           | 0.2713 | 0.012          |
| 5588.85377      | 2.115           | 0.988           | 0.1724 | 0.012          |
| 5663.60446      | 5.616           | 1.178           | 0.1918 | 0.012          |
| 5959.79501      | -3.994          | 1.019           | 0.2402 | 0.012          |
| 6284.83957      | -6.118          | 0.836           | 0.2481 | 0.012          |
| 6291.83583      | -7.558          | 0.829           | 0.1590 | 0.012          |
| 6345.74970      | -6.404          | 1.179           | 0.2418 | 0.012          |
| 6355.71078      | -2.553          | 1.206           | 0.3401 | 0.012          |

... ... ... ... ...

Table 2. PFS2 Radial Velocities of HD 95338. This table is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content.

| BJD (- 2450000) | RV (m s$^{-1}$) | $\sigma$ RV (m s$^{-1}$) | S (dex) | $\sigma$ S (dex) |
|-----------------|-----------------|-----------------|--------|----------------|
| 8471.81505      | 5.205           | 0.931           | 0.1644 | 0.008          |
| 8471.82063      | 3.733           | 0.892           | 0.1659 | 0.008          |
| 8473.82297      | 2.519           | 0.918           | 0.1690 | 0.008          |
| 8473.82677      | 2.613           | 0.910           | 0.1705 | 0.008          |
| 8474.85964      | 2.712           | 0.869           | 0.1770 | 0.008          |
| 8474.84550      | 1.512           | 0.839           | 0.1654 | 0.008          |
| 8475.84374      | 1.324           | 0.751           | 0.1586 | 0.008          |
| 8475.84752      | 0.202           | 0.784           | 0.1609 | 0.008          |
| 8476.82523      | -2.224          | 0.797           | 0.1631 | 0.008          |
| 8476.82897      | 1.295           | 0.785           | 0.1571 | 0.008          |
| 8479.84682      | -3.814          | 0.813           | 0.1623 | 0.008          |

... ... ... ... ...

Table 3. TERRA Radial Velocities of HD 95338

| BJD (- 2450000) | RV (m s$^{-1}$) | $\sigma$ RV (m s$^{-1}$) | S (dex) | $\sigma$ S (dex) |
|-----------------|-----------------|-----------------|--------|----------------|
| 8262.52210      | -2.347          | 0.963           | 0.1568 | 0.0016         |
| 8263.58809      | -2.716          | 0.555           | 0.1642 | 0.0011         |
| 8264.56962      | -2.820          | 0.775           | 0.1637 | 0.0014         |
| 8265.60191      | -2.412          | 0.677           | 0.1672 | 0.0012         |
| 8266.54165      | -4.199          | 1.105           | 0.1520 | 0.0018         |
| 8429.84914      | 0.0             | 0.706           | 0.1580 | 0.0011         |
| 8430.83705      | 1.651           | 0.712           | 0.1606 | 0.0009         |
| 8576.69728      | 12.654          | 1.156           | 0.1584 | 0.0016         |
| 8577.79238      | 14.113          | 1.479           | 0.1504 | 0.0023         |
| 8578.71982      | 11.102          | 0.853           | 0.1564 | 0.0013         |
| 8579.70958      | 11.115          | 0.790           | 0.1605 | 0.0012         |

3 STELLAR PARAMETERS

We derived [Fe/H], $T_{\text{eff}}$, age, mass, radius, log $g$ and $v\sin i$ using the spectral classification and stellar parameter estimation package SPECIES (Soto & Jenkins 2018), previously used in, e.g, Díaz et al. (2018); Díaz et al. (2020). In short, SPECIES derives $T_{\text{eff}}$, log $g$, [Fe/H], microturbulence, macroturbulence and rotational velocity, mass, age and chemical abundances automatically using a MCMC approach. These parameters are calculated from a high signal-to-noise, stacked spectrum from HARPS observations were we measure the equivalent widths for a set of iron lines. Macroturbulence and rotation velocity were computed by measuring the broadening of spectral lines using a Fourier analysis (see Soto & Jenkins 2018 for more details).
Then we performed a Spectral Energy Distribution (SED) fit to publicly available catalog photometry shown in Table 4 using the values found by SPECIES as priors.

The SED fit was done with ARIADNE, a python tool designed to automatically fit archival photometry to atmospheric model grids. Phoenix v2 (Husser et al. 2013), BT-Settl, BT-Cond (Allard et al. 2012), BT-NextGen (Hauschildt et al. 1999), Castelli & Kurucz (2003) and Kurucz (1993) stellar atmosphere models were convolved with different filter response functions, UBVRI; 2MASS JHKs (Skrutskie et al. 2006); SDSS griz; WISE W1 and W2; Gaia G, RP and BP; Pan-STARRS gizwyc; Strömgren uvby; GALEX NUV and FUV; TESS: Kepler; and NGTS to create 6 different model grids. We then model each SED by interpolating the model grids in $T_{\text{eff}}$ – log g – [Fe/H] space. The remaining parameters are distance, radius, extinction in the $V$ band, and individual excess noise terms for each photometry point in order to account for possible underestimated uncertainties or variability effects. We set priors for $T_{\text{eff}}$, log g, and [Fe/H] from the SPECIES results, for the radius we took Gaia DR2 radius values as prior, prior for the distance we used the Gaia parallax as priors after applying the Stassum & Torres (2016) correction, and we limited the $A_V$ to a maximum of 4.243 taken from the re-calibrated SFD galaxy dust map (Schlegel et al. 1998; Schlaflay & Finkbeiner 2011). Each excess noise parameter has a zero mean normal distribution as the prior, with the variance equal to five times the size of the reported uncertainty. We then performed the fit using dynesty’s nested sampler (Speagle 2019) to sample the posterior parameter space, obtaining the Bayesian evidence of each model and the marginalized posterior distribution for each fitted parameter as a by-product. Finally we averaged the posterior samples of each model, weighting each sample by its normalized evidence. To plot the SED, we selected the model grid with the highest evidence to calculate the synthetic photometry and overall model (Figure 1). We note the residuals from Figure 1 are normalized to the error of the photometry. In the case of precise photometry, e.g. Gaia, the residuals show a relatively high scatter. A more detailed explanation of the fitting procedure, accuracy, and precision of ARIADNE can be found in Vines & Jenkins (2020).

### 4 DETECTION FROM RADIAL VELOCITIES

We began examining the radial-velocity data by using the traditional periodogram analysis approach to look for any periodicities embedded in the data. We used the generalized version (Zechmeister & Kürster 2009) of the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982, hereafter GLS). Figure 2 shows the initial RV-only analysis where the signal at 55-days is clearly identified from the combined radial velocities. From this analysis we informed the following modeling process.

We modeled the radial velocities of HD 95338 following the same procedure defined in Tuomi et al. (2014) and performed in Jenkins & Tuomi (2014) and Díaz et al. (2018) with some slight variations in our model. We define the global model as follows:

\[
y_i,t = \tilde{y}_{i,t} + \epsilon_i,t + \eta_{i,t},
\]

where

\[
\tilde{y}_{i,t} = \gamma_j + f_k(t),
\]

is the deterministic part of the model composed of an offset $\gamma_j$ for data set $j$ and the Keplerian component

\[
f_k(t) = \sum_{m=1}^{K} K_m \cos(\omega_m t + \nu_m(t)) + e_m \cos(\omega_m t),
\]

which is a function that describes a $k$-Keplerian model with $K_m$ being the velocity semi-amplitude, $\omega_m$ is the longitude of pericenter, $\nu_m$ is the true anomaly and $e_m$ is the eccentricity. $\nu_m$ is also a function of the orbital period and the mean anomaly $M_{0,m}$.

---

Table 4. Stellar Parameters of HD 95338.

| Parameter          | Value         | Source        |
|--------------------|---------------|---------------|
| TESS Name          | TIC 30412124  | SIMBAD        |
| R.A. (J2000)       | 10:59:26.303  | SIMBAD        |
| Dec. (J2000)       | -56:37:22.947 | SIMBAD        |
| TESS               | 7.8436±0.0006 | ExoFOP\footnote{https://exofop.ipac.caltech.edu/tess/} |
| $H$                | 6.729±0.037   | 2MASS         |
| $J$                | 7.098±0.024   | 2MASS         |
| $K_s$              | 6.591±0.017   | 2MASS         |
| $V$                | 8.604±0.012   | Simbad        |
| $B$                | 9.487±0.013   | Simbad        |
| $G$                | 8.3821±0.0003 | Gaia          |
| $R_P$              | 7.8017±0.0013 | Gaia          |
| $B_P$              | 8.8464±0.0011 | Gaia          |
| W1                 | 6.55±0.071    | Wise          |
| W2                 | 6.578±0.023   | Wise          |
| Distance (pc)      | 36.94±0.03    | This work     |

---

\footnote{https://exofop.ipac.caltech.edu/tess/}
the model given the observed data we use Bayes’ rule: 

\[ P(\theta | y) \propto P(y | \theta) P(\theta) \int P(y | \theta) P(\theta) d\theta \]  

(5)

where \( P(y | \theta) \) is the likelihood function and \( P(\theta) \) corresponds to the prior. The denominator is a normalizing constant such that the posterior must integrate to unity over the parameter space. For our model, we choose the priors for the orbital and instrumental parameters as listed in Table 5.

For a given model, we sample the posterior through multiple tempered (hot) MCMC chains to identify the global maximum of the posterior. We then use non-tempered (cold) chains to sample the global maximum found by the hot chains. The procedure is similar to that previously done in Díaz et al. (2018) with the difference that here we do not model activity because it would introduce extra noise although it might remove some activity signals. From the posterior samples, we infer the parameter at the maximum a posteriori (MAP) and use quantiles to estimate parameter uncertainties. This is explained in detail in Feng et al. (2019). To select the optimal noise model, we calculate the maximum likelihood for a MA model using the Levenberg-Marquardt (LM) optimization algorithm (Levenberg 1944; Marquardt 1963).

We define the Bayes Factor comparing two given models, \( M_k \) and \( M_{k-1} \), as

\[ \ln B_{k,k-1} = \ln P(y | M_k) - \ln P(y | M_{k-1}) \]  

(6)

We calculate \( \ln(BF) \) for \( M_{A(q+1)} \) and \( M_{A(q)} \). If \( \ln(BF) < 5 \), we select \( M_{A(q)} \), according to Equation 6. If \( \ln(BF) \geq 5 \), we select \( M_{A(q+1)} \) and keep increasing the order of the MA model until the model with the highest order passing the \( \ln(BF) \geq 5 \) criterion is found. Considering that the Bayesian information criterion (BIC) is a good criterion for signal selection (Kass & Raftery 1995; Feng et al. 2016), we convert BIC to BF according to the formula given by Feng et al. (2016).

Our MCMC runs gave rise to the posterior histograms shown in Figure 3, where the period, amplitude, and minimum mass distributions show nice Gaussian forms centered on their respective values. We used the posterior distribution for \( T_{\text{peri}} \), the eccentricity and the longitude of pericenter, \( \omega \), to predict the transit time of the orbit, since the eccentric anomaly is defined as

\[ E = 2 \arctan(\sqrt{1 - e^2} \tan(\nu / 2)) \]

where \( \nu = \pi / 2 - \omega \) is the true anomaly. Then

\[ T_c = \frac{M}{2\pi} P + T_{\text{peri}} \]  

(7)

where

\[ M = E - e \sin(E) \]  

(8)

Then from our posterior distributions for \( T_{\text{peri}} \) (see Figure 3) we obtain \( T_c = 2458585.929 \pm 0.840 \) which turns out to be well in agreement, within uncertainties, with the ephemeris from the TESS photometry. \( T_c, T_{\text{ESS}} = 2458585.279 \) (see Table 7).

We note that additional tests were conducted using the Delayed Rejection Adaptive Metropolis algorithm (Metropolis et al. 1953; Haario et al. 2001, 2006), as previously done in Tuomi et al. (2014) and Díaz et al. (2018) and we found the results were in full agreement with the MA approach within the uncertainties.

### 5 STELLAR ACTIVITY AND RV CORRELATIONS

We computed the GLS periodogram of the combined S-indices from PFS1, PFS2 and HARPS (Figure 4). We do not find statistically significant periods from stellar activity matching the signal of the planet candidate (marked with a vertical line). However, we do see multiple peaks at ~1, ~29 and ~150 days above the 1% significance threshold. The 1-day period is likely due to the frequency of the sampling in the observations, similarly the 29 d peak is close to...
the lunar period. The additional 150 d period could be related to a stellar magnetic cycle, but more data is needed to test this hypothesis. Figure 5 shows the correlations between the mean-subtracted activity indices in the Mt. Wilson system, \( \Delta M_{\text{MW}} \), and the radial velocities: PFS1 (open triangles), PFS2 (black triangles) and HARPS (orange circles). We note the improvement in the scatter from PFS2 compared to PFS1; new activity indices are comparable to the scatter of those from HARPS, derived using the TERRA software. We see 4 points that are far off from the mean. We find the Pearson \( r \) correlation coefficients for PFS1, PFS2 and HARPS are 0.15, 0.38, -0.39, respectively, meaning no significant strong correlations are found (\(|r| < 0.5\)).

6 PHOTOMETRY

6.1 TESS Photometry

HD 95338 was observed by the Transiting Exoplanet Satellite Survey (TESS; Ricker et al. 2015). We checked the target was observed using the Web TESS Viewing Tool (WTV), as initially the target did not produce an alert on the TEV website where an overview table, alerts and downloadable data is available. We identified a single-transit in the TESS photometry from Sector 10 using camera 3 between March 26th 2019 and April 22nd 2019.

---

1 https://heasarc.gsfc.nasa.gov/cgi-bin/tess/webtess/wtv.py
2 https://tev.mit.edu/data/

---

Figure 3. Posterior distributions of the orbital parameters \( P, e, K, M_0, \omega, T_c, T_{\text{peri}} \) and minimum mass, respectively, obtained from our RV analysis. Dashed red lines on each plot show a Gaussian fit to the posterior distribution. \( T_c \) is derived from the time of pericenter passage values \( (T_{\text{peri}}, \text{see text}) \). Vertical black dashed line represents the transit time from the TESS lightcurve. From the histogram we found a mean value of \( T_c = 2458585.929 \) and \( \sigma = 0.84 \), which overlaps nicely with the transit time from the lightcurve, strongly indicating both signals originate from the same source.

Figure 4. Top: Time series of combined, mean subtracted S-indices from HARPS, PFS1 and PFS2. Bottom: GLS Periodogram of the S-indices. Vertical lines, from bottom to top, represent the 10, 1 and 0.1% significance thresholds levels estimated from 5000 bootstraps with replacement on the data.

We note that the star is located in a relatively crowded field, as \( \text{Gaia} \) returns 12 sources within an angular separation of 1 arcmin. Given that the pixels in the TESS cameras are 21 arcsec wide, this could mean some of the sources would contaminate the aperture. However, the brightest nearby source is \( G \sim 18 \text{ mag} \), which is 12
magnitudes fainter than HD 95338 that has a magnitude of $G = 8.38$. Converted into flux, this companion is ~7,500 times fainter than HD 95338. The transit has a depth of ~3000 ppm and this difference in flux would cause a depth of ~ 100 ppm, which we find it to be negligible compared to the transit depth.

We extracted the PDCSAP\_FLUX 2-minute cadence photometry following the same procedures we recently used in Diaz et al. (2020). The PDCSAP\_FLUX, median-corrected photometry is shown in the top panel of Figure 6. We then applied a median filter to remove the lightcurve variability, in particular on both sides near the transit event. The final flattened lightcurve is shown in the lower panel of Figure 6 and it is the transit data used throughout all our analyses.

Recent work by Sandford et al. (2019) have shown the use of single-transit lightcurves to estimate orbital periods based on precise parallaxes from Gaia. While their work focused on K2 data, we can apply the same methodology to our TESS lightcurve, since we also know the transit depth, and we can calculate the scaled semi-major axis and stellar density from the combination of the ARIADNE results and the high resolution spectra. We recall equations 1 and 2 from Sandford et al. (2019):

\[
p^2 = \frac{3\pi}{G} \left( \frac{a}{R_\star} \right)^3 \rho_\star \pm 1
\]

\[
\sigma_p = \frac{p}{2} \sqrt{\left( \frac{\sigma_a}{\rho_\star} \right)^2 + \left( \frac{3\pi a}{2R_\star} \rho_\star \right)^2}
\]

which yield the orbital period (and the associated error) of a single transit using Kepler’s third law and assuming circular orbits, where $G$ is the gravitation constant, $(a/R_\star)$ corresponds to the scaled semi-major axis measured directly from the shape of the transit and $\rho_\star$ is the stellar density that must come from an independent analysis. In our case, we used the stacked spectra acquired with HARPS, and from our spectra classification analysis with SPECIES combined with the SED fit, we find a stellar density of $\rho_\star = 1.68^{+0.45}_{-0.23}$ g cm\(^{-3}\). We estimate $(a/R_\star) = 58.06^{+3.39}_{-2.48}$ from the transit seen in the TESS lightcurve. Then, using equations (1) and (2) from Sandford et al. (2019) we get an estimate for an orbital period of 47±9 days for the single transit observed by TESS being consistent within the uncertainties to the period of the signal found in the radial velocity data.

6.2 ASAS Photometry

In an attempt to search for additional sources of periodicity we used data from the All Sky Automated Survey (ASAS; Pojmanski 1997). Figure 7 shows the photometry time series consisting on 625 measurements from December 7th 2000 to December 3rd 2009. We selected the best quality data, flagged as “A” or “B”. We used the GLS periodogram to search for signals after filtering the highest quality data from outliers, and found no statistically significant periods that could be attributed to the stellar rotation period, due in part to the size of the typical uncertainty in the ASAS photometry.

7 JOINT ANALYSIS

We performed a joint fit of the photometry and radial velocities using the juliet package (Espinosa et al. 2019) in order to estimate the orbital parameters for the system. To model the photometry juliet used the batman package (Kreidberg 2015) while the radial velocities are modeled using rv (Fulton et al. 2018). We then sampled the parameter space using the dynesty nested sampler (Speagle 2019) to compute posterior samples and model evidences. Initially we performed a TESS photometry-only analysis in order to estimate the depth and transit time for the transit using the period we estimated by using the stellar density from our spectroscopic analysis. We then included the radial velocities (Tables 1 to 3) and performed a joint model of the data setting the priors according to Table 6. We treated the eccentricity as a free parameter motivated by our finding from the RV-only analysis suggesting the eccentricity was different from zero. The resultant value was in agreement with the one from our previous analysis. The RV semi-amplitude prior was chosen as a flat prior between 1 and 100 to explore a wider range of amplitudes and not only values centered around the semi-amplitude found in the RV-only analysis. The jitter terms for PFS1, PFS2 and HARPS, were set using a Jeffreys prior over 2 orders of magnitude (0.1 to 10 m s\(^{-1}\)), resulting in excess RV noise of 2.3, 1.3 and 1.6 m s\(^{-1}\), respectively. The orbital period was constrained using a Gaussian prior centered at the period of the signal found in the RVs and with a width twice the errorbar from the MA analysis. The time of transit ($T_c$) was derived from the time of pericenter passage ($T_{peri}$) as discussed in Section 4.1. We used a Gaussian prior centered at our predicted $T_c$ with a width equal to standard deviation from the MA analysis. For the photometry parameters we used the efficient sampling for the transit depth ($p$) and impact parameter ($b$) described in Espinoza (2018) that allows only physically plausible values in the ($b,p$) plane to be sampled via the $r_1$ and $r_2$ coefficients according to the description of Kipping (2013) for two parameter laws. As a result we obtained a planet mass of $39.43^{+5.64}_{-5.39} M_\oplus$, consistent with a super-Neptune, with a radius of $3.98^{+0.09}_{-0.08} R_\oplus$ that translates to a relatively high density of $3.41^{+0.56}_{-0.40} g \text{ cm}^{-3}$ for this planet. We note here we did not use GPs nor MA as in the radial velocity-only analysis, so the residuals shown in 8 (right) are really the full residuals from a pure Keplerian model including instrumental jitter.

Figure 5. Radial velocity correlations vs S-indices from HARPS (circles), PFS1 (triangles), PFS2 (black triangles).

Figure 6. Summary of radial velocity analysis results. The top panel is the PDCSAP\_FLUX, median-corrected photometry, and the bottom panel is a median filtered lightcurve for a single transit observed by TESS being consistent with the transit depth.

Figure 7. The ASAS photometry time series (left) and the GLS periodogram (right) for the HJD range of the TESS lightcurve. The periodogram shows a peak near 76 days with a significance of 5.6 ppm.
We searched for additional signals by analyzing the residuals from the 1-planet fit. Figure 9 shows the GLS periodogram of the residual radial velocities for a 1-planet model. For this data, we do not find evidence for additional statistically significant signals present in the system after removing the 55-day planet signal. The peaks around ~1 and ~360 days are likely associated with the sampling of the radial velocities. However, more data will help to confirm or rule out additional companions, particularly given that the residual periodogram shows some weak evidence for a periodic signal around ~46 days.

9 DISCUSSION

In order to address how often we could recover a prediction for the transit centroid, $T_c$, that has an uncertainty of 1.5% of the orbital period or better, just as we see for HD 95338 b, we simulated $10^6$ systems with a single planet and random orbital parameters. We consider that all the random systems transit their host stars and...
we used flat priors for the distribution of longitude of pericenter, $\omega$, and for the eccentricity. For the distribution of orbital periods we used the broken power law presented in Mulders et al. (2018), where the break occurs at $P_b = 10$ days. For shorter periods the probability is written as $P(P/P_b)^{1.5}$, while for longer periods the probability is unity. For each system, we generated the remaining orbital parameters according to standard equations for $E, M, T_c$. Then we predicted $T_c$ according to equation 7 (see Section 4). We find that $\sim 9\%$ of the systems sampled randomly fulfill this criterion.

If the agreement between the RV prediction and transit $T_c$ found for HD 95338 is just a statistical fluke, then this means there are more planets in the system, since another body must give rise to the transit. The probability of $9\%$ does not consider this possibility. For that to be the case, we should also normalize by the fraction of confirmed Neptunes with known companions detected by the transit method by Kepler/K2 from the exoplanet.eu catalogue in a mass range between 10 and 40 $M_\oplus$. We find that the number of these multi-systems is 19 out of a total of 61, which corresponds to a fraction of $\sim 30\%$. This leads to a final probability of $\sim 3\%$, meaning it is highly unlikely that we have observed the configuration we find for HD 95338 b if the orbital parameters are randomly distributed. Even if Neptunes are indeed found to exist exclusively in multi-planet systems, there is still a $91\%$ probability that the RV detected companion and the TESS detected companion are the same object.

To better understand the composition of HD 95338 b, we have constructed interior structure models matched to its observed mass, radius, and orbital parameters. These models are explained in detail in Thorngren et al. (2016); briefly, they solve the equations of hydrostatic equilibrium, conservation of mass, and the material equation of state to determine the radius of a well-mixed planet. The equations of state (EOS) used were Chabrier et al. (2019) for H/He and a 50-50 ice-rock mixture from ANEOS (Thompson 1990) for the metals. Giant planets gradually cool by radiating away the residual heat left over from their initial formation, which we regulated using the atmosphere models of Fortney et al. (2007) to evolve the planets through time. Finally we used the Bayesian retrieval framework from Thorngren & Fortney (2019) to infer the bulk metallicities consistent with the planet parameters. The planet is cool enough that no anomalous heating effect should be present.

Our models show that to reproduce the planet’s high bulk density ($\rho_p = 3.41^{+0.56}_{-0.41}$ g cm$^{-3}$), a metallicity of $Z=0.9\pm0.02$ was required (see Figure 10). As such, it is among the most metal rich planets of this mass range, and raises questions about how the planet formation process can gather so much metals without also accreting more H/He. While extreme, this is not truly an outlier; other planets in this mass range are also found to have high metallicities (see Thorngren et al. 2016), including Kepler-413 b ($M_p = 0.21 M_J$, $Z = 0.89$, Kostov et al. 2014) and K2-27 b ($M_p = 0.09 M_J$, $Z = 0.84$, Van Eylen et al. 2016). It could be that these highly metallic, and massive planets, were formed through collisions with other worlds.

---

Table 7. Planetary Properties for HD 95338 b

| Property | Value |
|----------|-------|
| **Fitted Parameters** | |
| $P$ (days) | 55.086$^{+0.018}_{-0.019}$ |
| $T_0$ (BJD - 2450000) | 8585.279$^{+0.004}_{-0.002}$ |
| $a/R_\star$ | 58.062$^{+2.395}_{-2.480}$ |
| $b$ | 0.584$^{+0.048}_{-0.058}$ |
| $K$ (m s$^{-1}$) | 8.18$^{+0.40}_{-0.41}$ |
| $i_p$ (deg) | 89.34$^{+0.050}_{-0.077}$ |
| $e$ | 0.190$^{+0.025}_{-0.024}$ |
| $\omega$ (deg) | 26.12$^{+9.796}_{-10.563}$ |
| **Derived Parameters** | |
| $M_p$ ($M_\oplus$) | 39.43$^{+0.04}_{-0.11}$ |
| $R_p$ ($R_\oplus$) | 3.96$^{+0.09}_{-0.08}$ |
| $\rho_p$ (g cm$^{-3}$) | 3.41$^{+0.56}_{-0.41}$ |
| $T_{\text{eq}}$ (K) | 402$^{+260}_{-29}$ |
| $\langle F \rangle$ ($\times 10^7$ erg s$^{-1}$ cm$^{-2}$) | 1.27$^{+0.08}_{-0.08}$ |
| **Instrumental Parameters** | |
| $M_{\text{TESS}}$ (ppm) | -0.0000026$^{+0.00000002}_{-0.00000027}$ |
| $\sigma_{w,\text{TESS}}$ (ppm) | 1.776$^{+1.400}_{-1.508}$ |
| $q_{1,\text{TESS}}$ | 0.431$^{+0.107}_{-0.072}$ |
| $q_{2,\text{TESS}}$ | 0.854$^{+0.109}_{-0.192}$ |
| $\mu_{\text{PFS1}}$ (m s$^{-1}$) | 0.79$^{+0.35}_{-0.37}$ |
| $\sigma_{w,\text{PFS1}}$ (m s$^{-1}$) | 2.31$^{+0.33}_{-0.29}$ |
| $\mu_{\text{HARPS}}$ (m s$^{-1}$) | 2.85$^{+0.56}_{-0.60}$ |
| $\sigma_{w,\text{HARPS}}$ (m s$^{-1}$) | 1.60$^{+0.56}_{-0.40}$ |
| $\mu_{\text{PFS2}}$ (m s$^{-1}$) | -1.04$^{+0.27}_{-0.28}$ |
| $\sigma_{w,\text{PFS2}}$ (m s$^{-1}$) | 1.30$^{+0.30}_{-0.26}$ |

---

1Estimated using a Bond albedo of 0.5.

---

Figure 7. GLS periodogram for the ASAS V-band photometry. Horizontal lines mark the position of the 10.1 and 0.1% FAP threshold levels, from bottom to top, respectively. A peak close to $\sim 15$ days is seen in the power spectrum, however it is below any FAP threshold and cannot be considered as statistically significant.

---

3 http://exoplanet.eu/catalog/
10  M. R. Díaz et al.

Figure 8. Left: TESS lightcurve phased-folded to the period of 55 days. Solid line is the model for the transit. Bottom panel shows the residuals. Right: Phased-folded radial velocities from PFS1 (orange), HARPS (blue) and PFS2 (red) where the jitter has been added to the errobars. Solid black line represents the Keplerian model from the joint fit with juliet. The orbital parameters for the system are listed in Table 7.

Figure 9. GLS periodogram of the residuals for the 1-planet model from our joint fit with juliet. No statistically significant signals are seen after subtracting the 55-day period. However, additional observations would definitely confirm or rule out additional companions.

after the proto-planetary disk had dispersed, stripping the planet of gas whilst enriching it with further metals. Indeed the results here imply that the heavy element enrichment for HD 95338 b is of order $\sim 35 M_\oplus$. It is important to note that the radius measurement of this planet is sufficiently precise that modeling uncertainties are larger than statistical uncertainties. These principally include uncertainties in the EOS, the interior structure of the planet (core-dominated vs well mixed), and the rock-ice ratio of the metals. However, these uncertainties do not endanger the qualitative conclusion that the planet is extremely metal-rich, and changes would often lead to an even higher inferred $Z$.

10  CONCLUSIONS

We present the discovery of a dense Neptune planet, that is currently the longest period planet known to transit a star brighter than $V = 9$. Moreover it is the first single transit confirmed planet from the TESS mission. It orbits the early-K star, HD 95338, and was originally detected using long-term radial velocity measurements carried out as part of the Magellan/PFS Exoplanet Survey. Additional radial velocity data from HARPS help to further constrain the period and orbital parameters of the candidate. TESS photometry shows a single transit observed in Sector 10. From our orbital parameters we estimated the transit time, $T_c = 2458585.929 \pm 0.84$ and found it to be consistent within the errors with the observed transit by TESS, $T_c,_{TESS} = 2458585.279$, strongly suggesting both signals originate from the same source, and adding credibility to the reality of the planetary nature of the object. Planet structure models place HD 95338 b as a 100% ice world based on its mass and radius (see Figure 11). We estimated the heavy element content to be $Z = 0.9 \pm 0.02$, which translates to $\sim 35 M_\oplus$. Such a high metallic value requires work to explain. Follow-up observations are crucial to arrive at a better understanding of the properties of the

Figure 10. Corner plot showing the posteriors of heavy element content derived from the Bayesian retrieval framework described in Thorngren & Fortney (2019).
planet, and also to further constrain models for how such a world could form in the first place.

ACKNOWLEDGEMENTS

We thank N. Espinoza for useful discussion during the preparation of the manuscript. MRD acknowledges the support of CONICYT-PFCHA/Doctorado Nacional-21140646, Chile. JS acknowledges support from NASA's Planetary Atmospheres program. Funding for the TESS mission is provided by the NASA Explorer Program.

REFERENCES

Allard F., Homeier D., Freytag B., 2012, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370, 2765
Alonso-Floriano F. J., et al., 2019, A&A, 621, A74
Anderson E., Francis C., 2012, Astronomy Letters, 38, 331
Anglada-Escudé G., Butler R. P., 2012, ApJS, 200, 15
Baglin A., et al., 2006, in 36th COSPAR Scientific Assembly. p. 3749
Bakos G. Á., et al., 2013, PASP, 125, 154
Balint A., et al., 2013, in 36th COSPAR Scientific Assembly. p. 3749
Bakos G. Á., et al., 2013, ASP Conf. Ser., 448, 228
Balogh G. A., et al., 2013, A&A, 559, A32

Figure 11. Mass-radius diagram. Gray circles represent confirmed exoplanets from TEPcat (Southworth 2011) that have radius measurements with a precision of 20% or better. Neptune (blue) and Saturn (yellow) are included for comparison. Three isodensity curves are represented by the grey dashed lines. Composition models are from Fortney et al. (2007), and are shown by the coloured and labelled curves. The observed and derived parameters of HD 95338 b place this planet between a 100% ice world and a mixture of 50/50 ice-rock (see text).
