

## HATS-37Ab AND HATS-38b: TWO TRANSITING HOT NEPTUNES IN THE DESERT \*

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### ABSTRACT

We report the discovery of two transiting Neptunes by the HATSouth survey. The planet HATS-37Ab has a mass of  $0.099 \pm 0.042 M_J$  ( $31.5 \pm 13.4 M_{\oplus}$ ) and a radius of  $0.606 \pm 0.016 R_J$ , and is on a  $P = 4.3315$  days orbit around a  $V = 12.266 \pm 0.030$  mag,  $0.843^{+0.017}_{-0.012} M_{\odot}$  star with a radius of  $0.877^{+0.019}_{-0.012} R_{\odot}$ . We also present evidence that the star HATS-37A has an unresolved stellar companion HATS-37B, with a photometrically estimated mass of  $0.654 \pm 0.033 M_{\odot}$ . The planet HATS-38b has a mass of  $0.074 \pm 0.011 M_J$  ( $23.5 \pm 3.5 M_{\oplus}$ ) and a radius of  $0.614 \pm 0.017 R_J$ , and is on a  $P = 4.3750$  days orbit around a  $V = 12.411 \pm 0.030$  mag,  $0.890^{+0.016}_{-0.012} M_{\odot}$  star with a radius of  $1.105 \pm 0.016 R_{\odot}$ . Both systems appear to be old, with isochrone-based ages of  $11.46^{+0.79}_{-1.45}$  Gyr, and  $11.89 \pm 0.60$  Gyr, respectively. Both HATS-37Ab and HATS-38b lie in the Neptune desert and are thus examples of a population with a low occurrence rate. They are also among the lowest mass planets found from ground-based wide-field surveys to date.

**Keywords:** planetary systems — stars: individual ( HATS-37, GSC 6700-00149, HATS-38, GSC 6622-00794 ) techniques: spectroscopic, photometric

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\* The HATSouth network is operated by a collaboration consisting of Princeton University (PU), the Max Planck Institute für Astronomie (MPIA), the Australian National University (ANU), and Universidad Adolfo Ibáñez (UAI). The station at Las Campanas Observatory (LCO) of the Carnegie Institution for Science is operated by PU in conjunction with UAI, the station at the High Energy Spectroscopic Survey (H.E.S.S.) site is operated in conjunction with MPIA, and the station at Siding Spring Observatory (SSO) is operated jointly with ANU. Based in part on observations made with the MPG 2.2m Telescope at the ESO Observatory in La Silla. Based on observations collected at the European Southern Observatory under ESO programmes 094.C-0428(A), 095.C-0367(A), 097.C-0571(A), 098.C-0292(A), 099.C-0374(A), 0100.C-0406(A), 0100.C-0406(B). This paper includes data gathered with the 6.5 meter Magellan Telescopes at Las Campanas Observatory, Chile. Based in part on observations made with the Anglo-Australian Telescope operated by the Australian Astronomical Observatory.

## 1. INTRODUCTION

In the past two decades the population of known transiting exoplanets has grown at an accelerating pace, with the *Kepler* satellite (Borucki et al. 2010) dominating the overall number of discoveries. The distribution of the discoveries is far from homogeneous in terms of the planetary parameters, both due to observational biases and variations in the intrinsic occurrence of planets as a function of their physical parameters and those of their host stars. An example of an observational bias is the paucity of known transiting exoplanets with periods  $P \gtrsim 10$  days, a region of parameter space that the ground-based survey HATSouth (Bakos et al. 2013) was designed to target, and that is currently being explored efficiently by the Transiting Exoplanet Survey Satellite mission (*TESS*, Ricker et al. 2015). An example of intrinsically low occurrence rates is the so-called *Neptune desert*, a term coined by Mazeh et al. (2016) to describe a wedge in the period-mass or period-radius diagram where close-in ( $P \lesssim 5$  d) planets with radii similar to Neptune are very rare, and essentially non-existent for  $P \lesssim 3$  d (see also Szabó & Kiss 2011; Beaugé & Nesvorný 2013).

In order to uncover more planetary systems in sparsely populated regions such as the Neptune desert it pays to survey to fainter magnitudes than what *TESS* is optimized for. Ground based wide-field surveys currently operating such as HATSouth or NGTS (Wheatley et al. 2018) can provide that complement to *TESS* by uncovering an additional number of intrinsically rare systems. Indeed, one of the most extreme systems in the Neptune desert was recently uncovered by the NGTS (NGTS4-b, West et al. 2019). The reason for the existence of the desert is still a subject of active investigation. The physical processes thought to be relevant are photoevaporation and the tidal disruption barrier for gas giants after high-eccentricity migration (see Owen & Lai 2018, and references therein).

In this paper we report the discovery by the HATSouth survey of two transiting Neptunes in the desert. They both have similar values of radii and periods, and fairly similar masses. We thus contribute two more systems to the sparsely populated Neptune desert. The paper is structured as follows. In § 2 we describe the observational data which were used to perform the modeling of the system as described in § 3. The results are discussed in § 4.

## 2. OBSERVATIONS

Figures 1 and 2 show the observations collected for HATS-37 and HATS-38, respectively. Each figure shows the HATSouth light curve used to detect the tran-

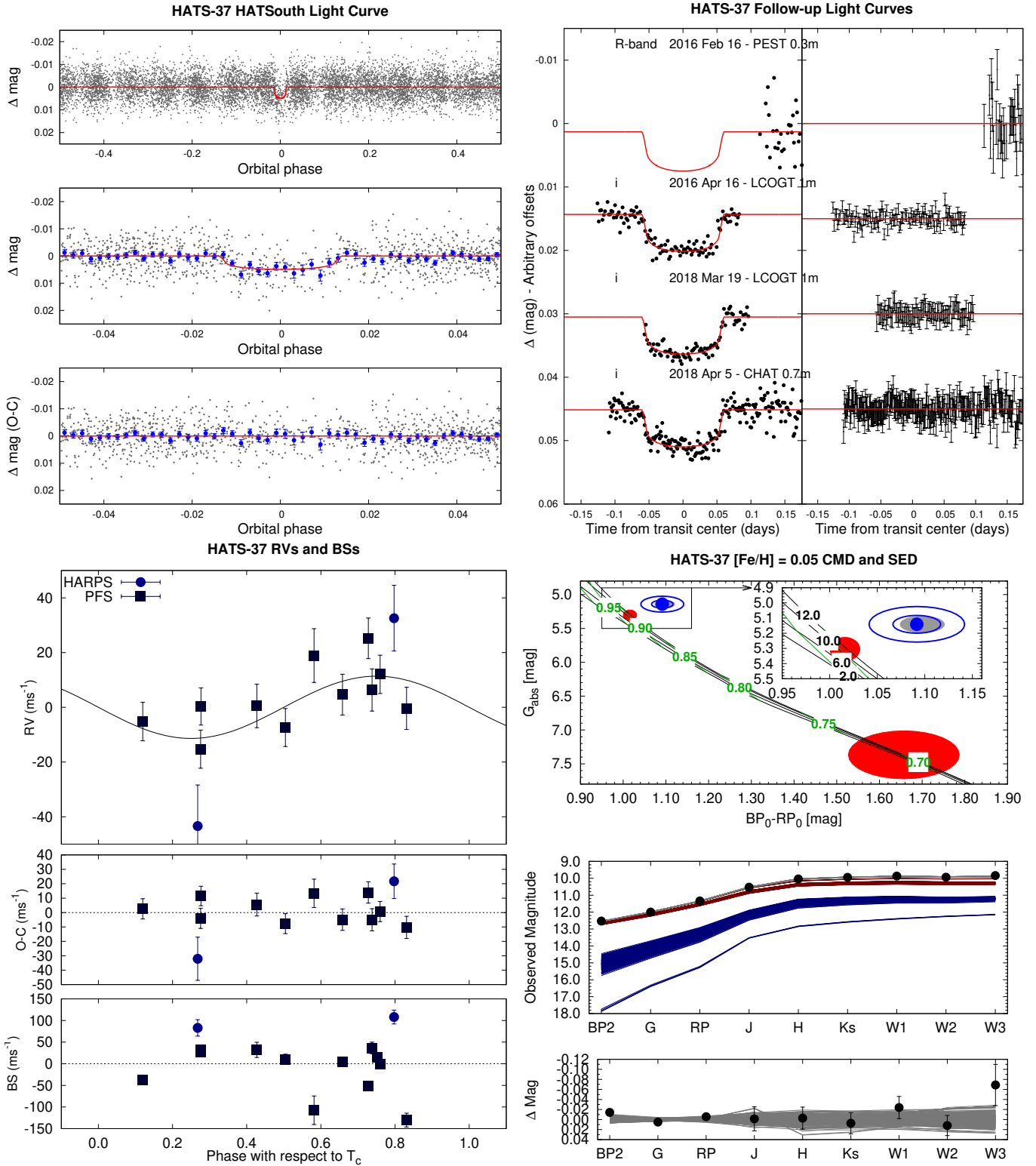
sits, the ground-based follow-up transit light curves, the high-precision radial velocities (RVs) and spectral line bisector spans (BSs), and the catalog broad-band photometry, including parallax corrections from Gaia DR2, used in characterizing the host stars. Below we describe the observations of these objects that were collected by our team.

### 2.1. Photometric detection

Both of the systems presented here were initially detected as transiting planet candidates based on observations by the HATSouth network. The operations of the network are described in Bakos et al. (2013), while our methods for reducing the data to trend-filtered light curves (filtered using the method of Kovács et al. 2005) and identifying transiting planet signals (using the Box-fitting Least Squares or BLS method; Kovács et al. 2002) are described in Penev et al. (2013). The HATSouth observations of each system are summarized in Table 1, while the light curve data are made available in Table 3.

We also searched the light curves for other periodic signals using the Generalized Lomb-Scargle method (GLS; Zechmeister & Kürster 2009), and for additional transit signals by applying a second iteration of BLS. Both of these searches were performed on the residual light curves after subtracting the best-fit primary transit models. No additional periodic signals are detected for HATS-37. For HATS-38 we detect a periodic signal at a period of  $P = 21.52$  day, semi-amplitude of 0.43 mmag, and a false alarm probability, determined via bootstrap simulations, of  $10^{-6.3}$ . We do not detect any additional transit signals in its light curve. The periodic signal detected for HATS-38 may correspond to the photometric rotation period of this  $T_{\text{eff}} = 5740 \pm 50$  K star. The star has  $v \sin i = 3.10 \pm 0.27$  km s $^{-1}$ , which gives an upper limit of  $18.7 \pm 1.7$  days on the equatorial rotation period. The photometric period of 21.52 days is  $1.7\sigma$  larger than this upper limit, but a larger value is possible if the rotation axis has  $\sin i \approx 1$  and the spots are at a latitude that is rotating more slowly than the equator.

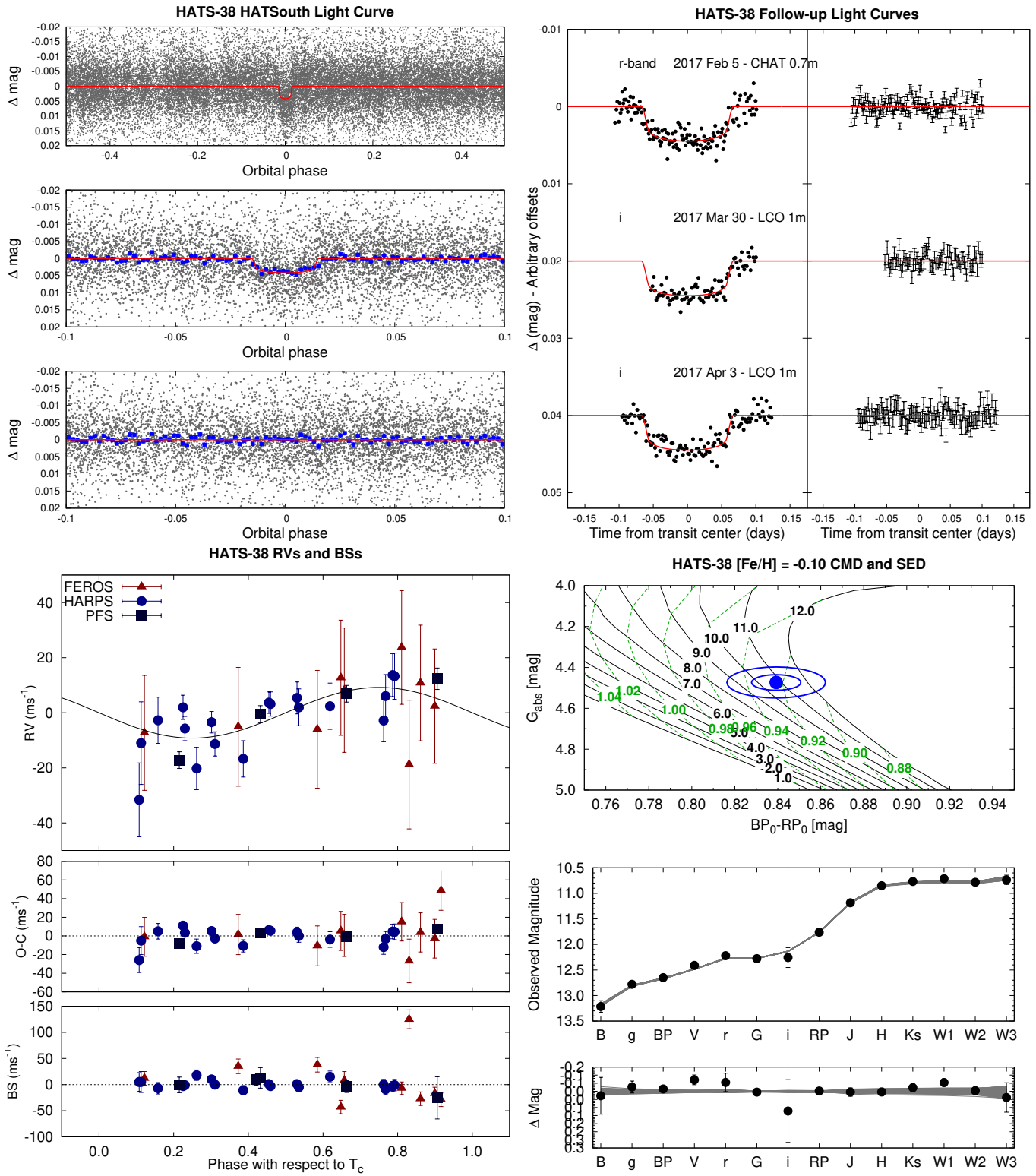
HATS-37  $P=4.33d$   $M_p=0.10M_{Jup}$   $R_p=0.61R_{Jup}$   $M_s=0.84M_{Sun}$   $R_s=0.88R_{Sun}$



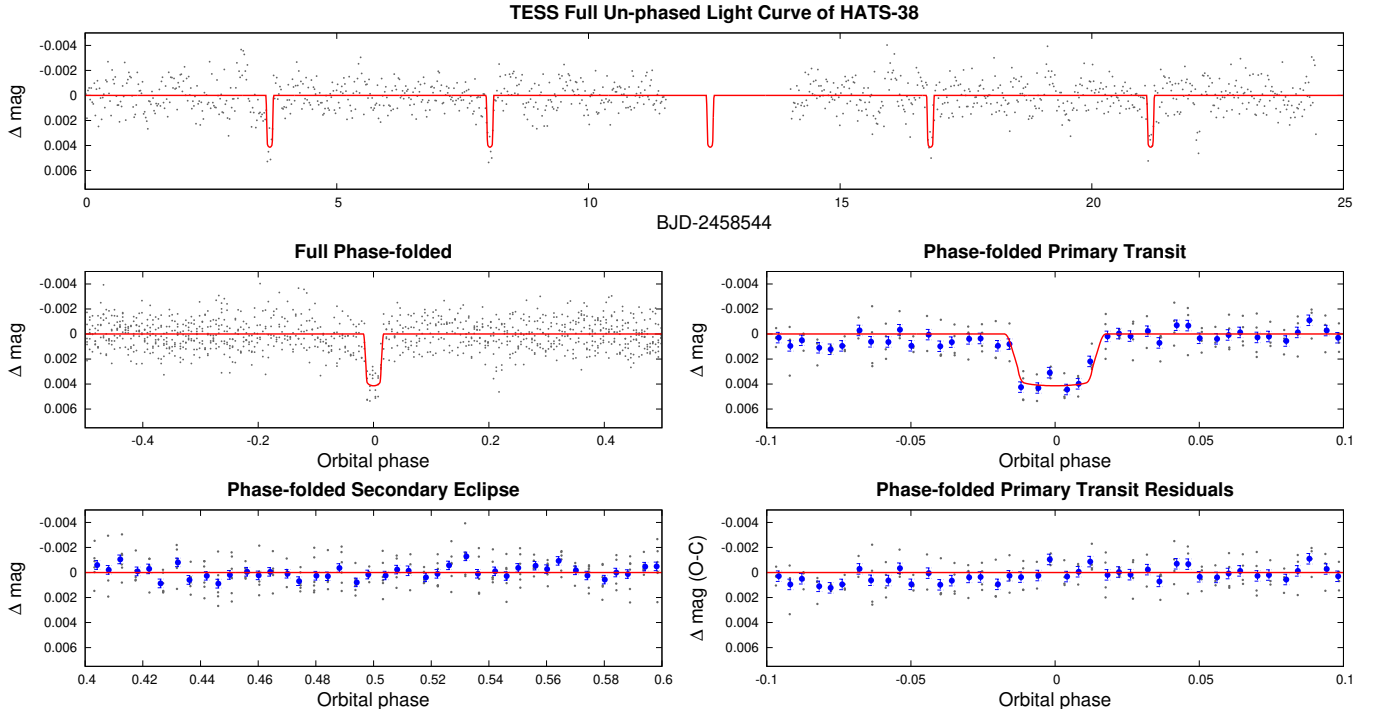
**Figure 1.** Observations used to confirm the transiting planet system HATS-37. *Top Left:* Phase-folded unbinned HATSouth light curve. The top panel shows the full light curve, the middle panel shows the light curve zoomed-in on the transit, and the bottom panel shows the residuals from the best-fit model zoomed-in on the transit. The solid lines show the model fits to the light curves. The dark filled circles show the light curves binned in phase with a bin size of 0.002. (Caption continued on next page).

**Figure 1.** (Caption continued from previous page) *Top Right:* Unbinned follow-up transit light curves corrected for instrumental trends fitted simultaneously with the transit model, which is overplotted. The dates, filters and instruments used are indicated. The residuals are shown on the right-hand-side in the same order as the original light curves. The error bars represent the photon and background shot noise, plus the readout noise. Note that these uncertainties are scaled up in the fitting procedure to achieve a reduced  $\chi^2$  of unity, but the uncertainties shown in the plot have not been scaled. *Bottom Left:* High-precision RVs phased with respect to the mid-transit-time. The instruments used are labelled in the plot. The top panel shows the phased measurements together with the best-fit model. The center-of-mass velocity has been subtracted. Both the observations and the model have also had a linear trend in time subtracted (Fig. 4). In this case the model has not been corrected for dilution from the unresolved stellar component HATS-37B. We find that the dilution corrected orbit has a semi-amplitude that is  $\sim 20\%$  larger than what is shown here. The second panel shows the velocity  $O-C$  residuals. The error bars include the estimated jitter. The third panel shows the bisector spans. *Bottom Right:* Color-magnitude diagram (CMD) and spectral energy distribution (SED). The top panel shows the absolute  $G$  magnitude vs. the de-reddened  $BP - RP$  color compared to theoretical isochrones (black lines) and stellar evolution tracks (green lines) from the PARSEC models interpolated at the best-estimate value for the metallicity of the host. The age of each isochrone is listed in black in Gyr, while the mass of each evolution track is listed in green in solar mass units. The filled blue circles show the measured reddening- and distance-corrected values from Gaia DR2, while the blue lines indicate the  $1\sigma$  and  $2\sigma$  confidence regions, including the estimated systematic errors in the photometry. Here we model the system as a binary star with a planet transiting one component. The  $1\sigma$  posterior distributions for the primary star HATS-37A and secondary star HATS-37B are shown as the red ellipses. The gray ellipse shows the  $1\sigma$  posterior distribution for the combined photometry of the system. The inset shows a zoomed-in view around the primary star and the combined photometry. The middle panel shows the SED as measured via broadband photometry through the listed filters. Here we plot the observed magnitudes without correcting for distance or extinction. Overplotted are 200 model SEDs randomly selected from the MCMC posterior distribution produced through the global analysis (gray lines). The SEDs of the primary and secondary components are also shown with red and blue lines, respectively. Note that the solution has two modes. The first mode consists of a primary star with mass  $0.84 M_{\odot}$ , and a secondary star with mass  $0.65 M_{\odot}$ . The second mode consists of a primary star with mass  $0.88 M_{\odot}$ , and a fainter secondary star with mass  $0.48 M_{\odot}$ . The first mode is  $\sim 35$  times more likely based on its representation in the posterior distribution. The model makes use of the predicted absolute magnitudes in each bandpass from the PARSEC isochrones, the distance to the system (constrained largely via Gaia DR2) and extinction (constrained from the SED with a prior coming from the MWDUST 3D Galactic extinction model). The bottom panel shows the  $O-C$  residuals from the best-fit model SED.

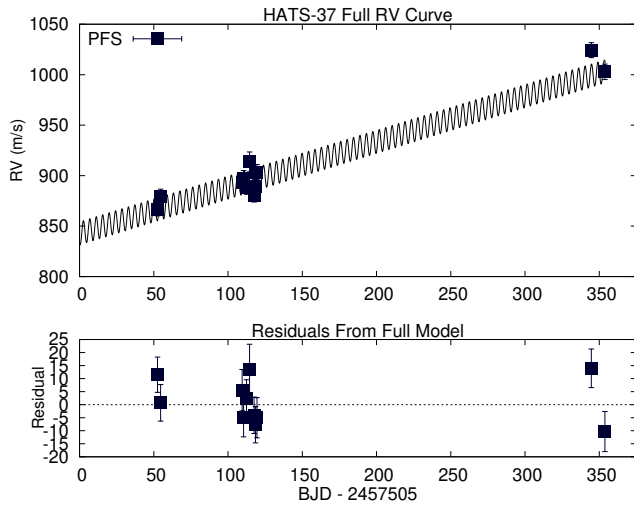
HATS-38  $P=4.38\text{d}$   $M_p=0.07M_{\text{Jup}}$   $R_p=0.61R_{\text{Jup}}$   $M_s=0.89M_{\text{Sun}}$   $R_s=1.10R_{\text{Sun}}$



**Figure 2.** Same as Figure 2, here we show the observations of HATS-38 when modelled as a single star with a transiting planet.



**Figure 3.** *Top:* Unbinned *TESS* observations of HATS-38 plotted against time simultaneously with the transit model, which is overplotted. *Middle:* Phase-folded unbinned *TESS* light curve. The left panel shows the full light curve, the right panel shows the light curve zoomed-in on the transit. The solid lines show the model fits to the light curves. The blue filled circles in the middle right panel show the light curve binned in phase with a bin size of 0.002. *Bottom:* Phase-folded *TESS* light curve around the predicted time of secondary eclipse (left panel) and residuals with respect to the transit model shown in the middle right panel. The black dots show the unbinned data, while the blue filled circle show values binned in phase with a bin size of 0.002.



**Figure 4.** *Top:* RV observations of HATS-37 plotted against time. The solid line shows the best-fit model including a linear trend and the Keplerian orbital variation of the host star due to the planet HATS-37Ab. As in Figure 1, the RV model plotted here is not corrected for dilution from the unresolved stellar component HATS-37B. The corrected semi-amplitude of the orbit is  $\sim 20\%$  larger than what is shown. *Bottom:* RV residuals from the best-fit model plotted against time.

**Table 1.** Summary of photometric observations

Instrument/Field <sup>a</sup>	Date(s)	# Images	Cadence <sup>b</sup> (sec)	Filter	Precision <sup>c</sup> (mmag)
<b>HATS-37</b>					
HS-1/G567.1	2011 Mar–2011 Aug	4975	294	<i>r</i>	5.2
HS-3/G567.1	2011 Jul–2011 Aug	735	297	<i>r</i>	5.7
HS-5/G567.1	2011 Mar–2011 Aug	3217	291	<i>r</i>	5.0
PEST 0.3 m	2016 Feb 16	113	132	$R_C$	2.8
Swope 1 m/e2v	2017 Apr 04	161	104	<i>i</i>	1.6
LCO 1 m/sinistro	2016 Apr 16	108	159	<i>i'</i>	1.0
LCO 1 m/sinistro	2018 Mar 19	82	163	<i>i'</i>	0.8
CHAT 0.7 m	2018 Apr 05	217	113	<i>i</i>	1.4
<b>HATS-38</b>					
HS-1/G561.1	2014 Dec–2015 Jul	4892	319	<i>r</i>	6.7
HS-2/G561.1	2014 Dec–2015 Jul	5718	349	<i>r</i>	4.7
HS-3/G561.1	2014 Dec–2015 Jul	3691	353	<i>r</i>	5.1
HS-4/G561.1	2014 Dec–2015 Jul	2862	352	<i>r</i>	6.9
HS-5/G561.1	2014 Dec–2015 Jul	2959	356	<i>r</i>	5.7
HS-6/G561.1	2014 Dec–2015 Jul	3058	342	<i>r</i>	6.9
HS-1/G561.1.focus	2014 Dec–2015 Jul	2026	1122	<i>r</i>	14.5
HS-2/G561.1.focus	2014 Dec–2015 Jul	2134	1204	<i>r</i>	13.4
HS-3/G561.1.focus	2014 Dec–2015 Jul	1217	1227	<i>r</i>	14.1
HS-4/G561.1.focus	2014 Dec–2015 Jul	977	1221	<i>r</i>	15.5
HS-5/G561.1.focus	2014 Dec–2015 Jul	1190	1232	<i>r</i>	15.0
HS-6/G561.1.focus	2014 Dec–2015 Jul	1174	1206	<i>r</i>	15.7
CHAT 0.7 m	2017 Feb 05	146	112	<i>r</i>	1.1
LCO 1 m/sinistro	2017 Mar 30	83	161	<i>i'</i>	0.9
LCO 1 m/sinistro	2017 Apr 03	118	160	<i>i'</i>	1.0

<sup>a</sup> For HATSouth data we list the HATSouth unit, CCD and field name from which the observations are taken. HS-1 and -2 are located at Las Campanas Observatory in Chile, HS-3 and -4 are located at the H.E.S.S. site in Namibia, and HS-5 and -6 are located at Siding Spring Observatory in Australia. Each unit has 4 CCDs. Each field corresponds to one of 838 fixed pointings used to cover the full  $4\pi$  celestial sphere. All data from a given HATSouth field and CCD number are reduced together, while detrending through External Parameter Decorrelation (EPD) is done independently for each unique unit+CCD+field combination. For HATS-38 we also derived light curves from short (30 s) focus frames that were taken by the HATSouth instruments every  $\sim 20$  minutes. The Swope 1 m light curve for HATS-37 covered a predicted secondary eclipse event.

<sup>b</sup> The median time between consecutive images rounded to the nearest second. Due to factors such as weather, the day–night cycle, guiding and focus corrections the cadence is only approximately uniform over short timescales.

<sup>c</sup> The RMS of the residuals from the best-fit model.

## 2.2. Spectroscopic Observations

The spectroscopic observations carried out to confirm and characterize both of the transiting planet systems are summarized in Table 2. The facilities used include FEROS on the MPG 2.2 m (Kaufer & Pasquini 1998), Coralie on the Euler 1.2 m (Queiroz et al. 2001), HARPS on the ESO 3.6 m (Mayor et al. 2003), WiFeS on the ANU 2.3 m (Dopita et al. 2007) and PFS on the Magellan 6.5 m (Crane et al. 2006, 2008, 2010).

The FEROS, Coralie, and HARPS observations were reduced to wavelength-calibrated spectra and high-precision RV and Bisector Span (BS) measurements using the CERES pipeline (Brahm et al. 2017a).

The WiFeS observations of HATS-37, which were used for reconnaissance, were reduced following Bayliss et al. (2013). We obtained a single spectrum at resolution  $R \equiv \Delta\lambda/\lambda \approx 3000$  from which we estimated the effective temperature,  $\log g$  and  $[\text{Fe}/\text{H}]$  of the star. Three observations at  $R \approx 7000$  were also obtained to search



for any large amplitude radial velocity variations at the  $\sim 4 \text{ km s}^{-1}$  level, which would indicate a stellar mass companion.

The PFS observations of both HATS-37 and HATS-38 include observations through an  $\text{I}_2$  cell, and observations without the cell used to construct a spectral template. The observations were reduced to spectra and used to determine high precision relative RV measurements following Butler et al. (1996). Spectral line bisector spans and their uncertainties were measured as described by Jordán et al. (2014) and Brahm et al. (2017a).

We also used the HARPS and  $\text{I}_2$ -free PFS observations to determine high-precision stellar atmospheric parameters, including the effective temperature  $T_{\text{eff}\star}$ , surface gravity  $\log g$ , metallicity  $[\text{Fe}/\text{H}]$ , and  $v \sin i$  via the ZASPE package (Brahm et al. 2017b). For HATS-37 we used the PFS observations to perform this analysis, while for HATS-38 this analysis was performed on the HARPS observations.

The high-precision RV and BS measurements are given in Table 7 for both systems at the end of the paper.

### 2.3. Photometric follow-up observations

Follow-up higher-precision ground-based photometric transit observations were obtained for both systems, as summarized in Table 1. The facilities used for this purpose include: the Chilean-Hungarian Automated Telescope (CHAT) 0.7 m telescope at Las Campanas Observatory, Chile (Jordán et al. 2018); 1 m telescopes from the Las Cumbres Observatory (LCO) network, (Brown et al. 2013); the 0.3 m Perth Exoplanet Survey Telescope in Australia (PEST)<sup>1</sup>; and the Swope 1 m telescope at Las Campanas Observatory in Chile.

Our methods for carrying out the observations with these facilities and reducing the data to light curves have been described in our previous papers (Penev et al. 2013; Mohler-Fischer et al. 2013; Bayliss et al. 2013; Jordán et al. 2014; Hartman et al. 2015; Rabus et al. 2016; Hartman et al. 2019).

The time-series photometry data are available in Table 3, and are plotted for each object in Figures 1 and 2.

### 2.4. TESS light curves

During its primary mission, *TESS* observed both of our targets. HATS-37 (TIC6036597) was observed on Sector 10, CCD 3 of camera 1, but the source lies within the bleed of a nearby bright star making the photometry unusable. HATS-38 (TIC168281028) was observed by the *TESS* primary mission during its first year of

operations. The target star fell on Camera 2, CCD 4 of the Sector 9 observations. Photometry was extracted from the Science Processing Operations Center (SPOC Jenkins et al. 2016) calibrated Full Frame Images (FFI), retrieved via the MAST *tesscut* tool. Aperture photometry was performed using selected pixels of a  $7 \times 7$  pixel cutout of the FFIs with the *lightkurve* package (Bartensen et al. 2019). The background flux was estimated from the remainder pixels that excluded nearby stars. We corrected for the flux contribution from nearby stars within our photometric aperture. A list of nearby stars was queried from the TICv8 catalogue (Stassun et al. 2019), and their flux contributions to the photometric aperture was computed assuming each star has a Gaussian profile with FWHM of 1.63 pixels, as measured from the *TESS* pixel response function at the location of the target star. The *TESS* light curve for HATS-38 is shown in Figure 3.

### 2.5. Search for Resolved Stellar Companions

The Gaia DR2 catalog provides the highest spatial resolution optical imaging for both of these targets. Gaia DR2 is sensitive to neighbors with  $G \lesssim 20$  mag down to a limiting resolution of  $\sim 1''$  (e.g., Ziegler et al. 2018). We find that neither object has a resolved neighbor in the Gaia DR2 catalog within  $10''$ .

For HATS-38 we also obtained  $J$  and  $K_S$ -band images using the WIYN High-Resolution Infrared Camera (WHIRC) on the WIYN 3.5 m telescope at Kitt Peak National Observatory (KPNO) in Arizona. The observations were carried out on the night of 2018 March 18, and have an effective full-width at half maximum (FWHM) of  $0''.43$  in  $J$  and  $0''.35$  in  $K_S$ . The images were collected at four different nod positions in each filter. These were calibrated, background-subtracted, registered and median-combined using the FITSH software package (Pál 2012).

We find a faint source separated from HATS-38 by  $6''$ . The source is detected at about  $\sim 3\sigma$  confidence in both bands, and has a magnitude contrast of  $\Delta J = 8.05 \pm 0.09$  mag and  $\Delta K_S = 7.18 \pm 0.08$  mag compared to HATS-38. The object is too faint, and too distant from HATS-38 to be responsible for the transit signal. The  $J$  and  $K_S$  magnitudes are consistent with it being a  $0.09 M_\odot$  star that is physically bound to HATS-38, at a current projected separation of  $\sim 2100$  AU. In that case the source would have  $G \sim 23$  mag, consistent with the object not being included in Gaia DR2. It could also be an extragalactic source, an earlier M dwarf star that is in the background of HATS-38, or a foreground brown dwarf.

<sup>1</sup> <http://pestobservatory.com/>

**Table 2.** Summary of spectroscopy observations.

Instrument	UT Date(s)	# Spec.	Res. $\Delta\lambda/\lambda/1000$	S/N Range <sup>a</sup>	$\gamma_{RV}$ <sup>b</sup> ( $\text{km s}^{-1}$ )	RV Precision <sup>c</sup> ( $\text{m s}^{-1}$ )
<b>HATS-37</b>						
ANU 2.3 m/WiFeS	2014 Feb 20	1	3	35	...	...
ANU 2.3 m/WiFeS	2014 Feb 20–23	3	7	38–72	8.2	4000
Euler 1.2 m/Coralie	2014 Mar–2016 Jun	6	60	20–29	7.05	149
ESO 3.6 m/HARPS	2016 Feb 27–29	2	115	19–22	6.417	38
Magellan 6.5 m/PFS+I <sub>2</sub>	2016 Jun–2017 Apr	11	76	...	...	8.7
Magellan 6.5 m/PFS	2016 Jun 20	1	76	...	...	...
<b>HATS-38</b>						
Euler 1.2 m/Coralie	2016 Nov 16–18	3	60	17–20	4.143	54
ESO 3.6 m/HARPS	2016 Nov–2017 May	18	115	17–47	4.144	9.2
MPG 2.2 m/FEROS	2016 Dec–2017 Mar	10	48	36–67	4.130	19
Magellan 6.5 m/PFS+I <sub>2</sub>	2017 Apr 5–8	4	76	...	...	5.7
Magellan 6.5 m/PFS	2017 Apr 19	1	76	...	...	...

<sup>a</sup> S/N per resolution element near 5180 Å. This was not measured for all of the instruments.

<sup>b</sup> For high-precision RV observations included in the orbit determination this is the zero-point RV from the best-fit orbit. For other instruments it is the mean value. We only provide this quantity when applicable.

<sup>c</sup> For high-precision RV observations included in the orbit determination this is the scatter in the RV residuals from the best-fit orbit (which may include astrophysical jitter), for other instruments this is either an estimate of the precision (not including jitter), or the measured standard deviation. We only provide this quantity when applicable.

No other sources are detected closer to HATS-38 in the WIYN/WHIRC images. Fig. 5 shows the resulting  $5\sigma$  contrast curves for HATS-38. These curves were generated using the tools described by Espinoza et al. (2016). We can rule out neighbors with  $\Delta J < 3$  mag and  $\Delta K_s < 3$  mag at a separation of  $0''.5$ , and  $\Delta J < 7$  mag and  $\Delta K_s < 6$  mag at a separation of  $1''.5$ .

### 3. ANALYSIS

We analyzed the photometric and spectroscopic observations of each system to determine the stellar and planetary parameters following the methods described in Hartman et al. (2019), with modifications as summarized most recently in Bakos et al. (2018). Briefly, the modelling involves performing a global fit of all the light curves and RV curves described in section 2, spectroscopically measured stellar atmospheric parameters, catalog broad-band photometry, and stellar parallax using a Differential Evolution Markov Chain Monte Carlo (DEMCMC) method. We fit the observations in two modes: (1) using an empirical method to determine the stellar mass given the direct observational constraint on the stellar radius and bulk density; and (2) constraining the stellar physical parameters using the PARSEC stellar evolution models (Marigo et al. 2017). We use the MWDUST Galactic extinction model (Bovy et al. 2016)

to place a prior constraint on the line of sight extinction, but we allow the value to vary in the fit.

We also performed a blend modelling of each system following Hartman et al. (2019), where we attempt to fit all of the observations, except the RV data, using various combinations of stars, with parameters constrained by the PARSEC models. This is done both to rule out blended stellar eclipsing binary scenarios, and to identify systems that may have an unresolved stellar companion. For the blend modelling we consider five scenarios: (1) a single star with a transiting planet (the H-p scenario); (2) an unresolved binary star system with a transiting planet around the brighter stellar component (the H-p,s scenario); (3) an unresolved binary star system with a transiting planet around the fainter stellar component (the H,s-p scenario); (4) a hierarchical triple star system consisting of a bright star and a fainter eclipsing binary system (the H,s-s scenario); and (5) a blend between a bright foreground star, and a background stellar eclipsing binary system (the H,s-SBGEb scenario). For each case we perform an initial grid search over the most difficult to optimize parameters to find the global maximum likelihood (ML) fit, and then perform a DEMCMC analysis, initializing the chain near the ML location. As part of this analysis we also predict spectral line bisector span (BS) measurements, and RV measurements from the composite system. These are compared to the ob-

**Table 3.** Light curve data for HATS-37 and HATS-38.

Object <sup>a</sup>	BJD <sup>b</sup>	Mag <sup>c</sup>	$\sigma_{\text{Mag}}$	Mag(orig) <sup>d</sup>	Filter	Instrument
HATS-37	2455765.23265	0.00383	0.00267	...	<i>r</i>	HS
HATS-37	2455691.59689	-0.00538	0.00294	...	<i>r</i>	HS
HATS-37	2455678.60275	0.00353	0.00337	...	<i>r</i>	HS
HATS-37	2455747.90786	0.00160	0.00295	...	<i>r</i>	HS
HATS-37	2455682.93494	-0.00208	0.00250	...	<i>r</i>	HS
HATS-37	2455665.61003	-0.00583	0.00305	...	<i>r</i>	HS
HATS-37	2455708.92562	0.00583	0.00249	...	<i>r</i>	HS
HATS-37	2455691.60029	0.00317	0.00300	...	<i>r</i>	HS
HATS-37	2455652.61745	-0.00718	0.00291	...	<i>r</i>	HS
HATS-37	2455747.91127	0.00013	0.00262	...	<i>r</i>	HS

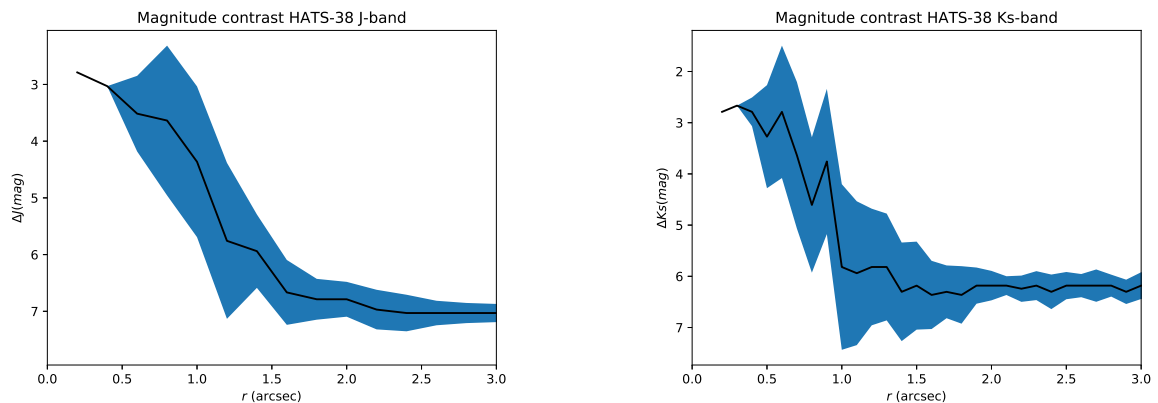
<sup>a</sup> Either HATS-37 or HATS-38.

<sup>b</sup> Barycentric Julian Date is computed directly from the UTC time without correction for leap seconds.

<sup>c</sup> The out-of-transit level has been subtracted. For observations made with the HAT-South instruments (identified by “HS” in the “Instrument” column) these magnitudes have been corrected for trends using the EPD and TFA procedures applied *prior* to fitting the transit model. This procedure may lead to an artificial dilution in the transit depths. The blend factors for the HATSouth light curves are listed in Table 6. For observations made with follow-up instruments (anything other than “HS” in the “Instrument” column), the magnitudes have been corrected for a quadratic trend in time, and for variations correlated with up to three PSF shape parameters, fit simultaneously with the transit.

<sup>d</sup> Raw magnitude values without correction for the quadratic trend in time, or for trends correlated with the seeing. These are only reported for the follow-up observations.

NOTE— This table is available in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.



**Figure 5.**  $5\sigma$  contrast curve for HATS-38 based on our WIYN/WHIRC *J*-band (*left*) and *K<sub>S</sub>*-band (*right*) observations. In each case the blue band shows the variation in the limit in azimuth at a given radius.

served RV and BS measurements to rule out any blend scenarios that, while consistent with the photometric observations, predict much larger RV and BS variations than observed. For blend scenarios containing a transiting planet, we use these simulated RV observations to determine a scaling factor by which we expect the

RV semi-amplitude  $K$  to be reduced by dilution from the stellar companion. We then use this factor to scale the value of  $K$  determined from our H-p model of the RV observations to obtain corrected values for the H-p,s and H-s,p models. We assume a 20% uncertainty on the scaling factor.

For HATS-37 we find that the H-p,s scenario provides the best fit to the photometric data, with  $\chi_{H-p,s}^2 - \chi_{H-p}^2 = -296$  and  $\chi_{H-p,s}^2 - \chi_{H,s-s,BGEB}^2 = -166$ , and even greater improvements relative to the H,s-s and H,s-p scenarios. Based on this we conclude that HATS-37 is not a blended stellar eclipsing binary object, but rather is best interpreted as a star with a transiting planet and a fainter, unresolved stellar companion. Note that here the use of the MWDUST Galactic extinction model is critical in coming to this conclusion. When the extinction is allowed to vary without the constraint, we find that the H,s-SBGEB scenario provides a slightly better fit to the data than the H-p,s model, while the improvement of the H-p,s model compared to the H-p model is less significant. These models, however, require much greater extinction ( $A_V > 3$  mag in the case of the H,s-SBGEB model, and  $A_V \sim 1$  mag in the case of the H-p model) that is at odds with the total line of sight extinction of 0.274 mag based on dust maps. The best-fit H-p,s model, however, yields  $A_V = 0.258 \pm 0.062$  mag, which is in good agreement with the dust maps.

In addition to the photometric evidence for an unresolved stellar companion to HATS-37A, we also find evidence for such a companion in the RV observations. The PFS RVs of this system show a strong linear trend of  $0.4539 \pm 0.0015 \text{ m s}^{-1} \text{ d}^{-1}$  (Figure 4). We included this trend, together with a Keplerian orbit for the transiting system, in our modeling of the RV observations. If the trend corresponds to the line-of-sight acceleration of HATS-37A due to HATS-37B, then given the estimated mass of  $0.654 \pm 0.033 M_\odot$  from our H-p,s model, we can place an upper limit on the current physical separation between the two stars of  $a_{AB} < 27.2 \text{ AU}$ . This upper limit corresponds to the case where there is no projected separation between the two stars. The maximum projected separation consistent with this acceleration is  $a_{AB,\text{proj}} < 16.9 \text{ AU}$ , corresponding to a maximum current angular separation between the stars of  $\theta_{AB} < 0''.08$ .

For HATS-38 we find that the H-p, H-p,s and H,s-SBGEB models provide comparable fits to the photometric data, with  $\chi_{H-p}^2 - \chi_{H-p,s}^2 = 7.0$  and  $\chi_{H-p}^2 - \chi_{H,s-s,BGEB}^2 = 5.8$ . These differences are comparable to the  $1\sigma$  scatter in  $\chi^2$  for a given model as measured from the Markov Chains, and consistent with the slight improvement in the fit for the H,s-SBGEB and H-p,s models being solely due to the increased complexity of these models. In this case we make use of the RV and BS observations to rule out the H,s-SBGEB model. The simulated HARPS RV and BS observations for the H,s-SBGEB model show significantly larger variations than observed, with the simulated RV RMS in excess of  $200 \text{ m s}^{-1}$ , and

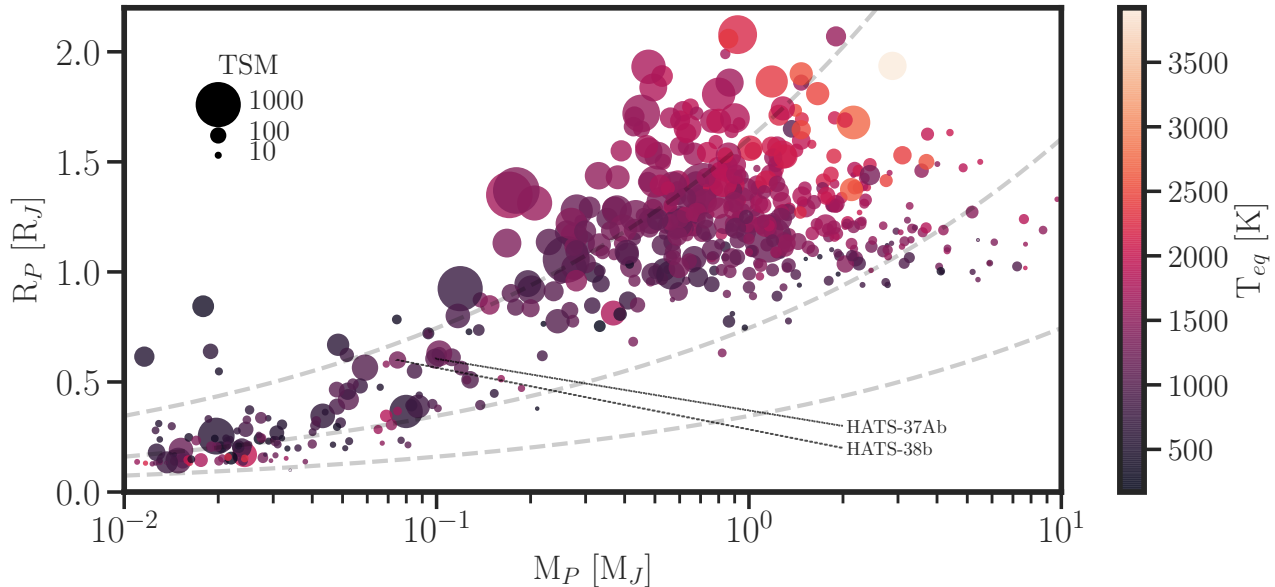
the simulated BS RMS in excess of  $300 \text{ m s}^{-1}$ . The actual HARPS RV and BS observations have RMS scatters of only  $12 \text{ m s}^{-1}$  and  $8 \text{ m s}^{-1}$ , respectively, with the RV observations following a Keplerian orbit as expected for a the case of a transiting planet system. We can also rule out the H,s-s and H,s-p models based on the photometry as these both provide significantly worse fits to the data than the H-p model. Since the H-p,s model does not provide a significant improvement over the H-p model, we choose to adopt the parameters for the system assuming it is a single star with a transiting planet. We place a 95% confidence upper limit on the mass of any unresolved companion star of  $M_B < 0.62 M_\odot$ . If we adopted the H-p,s model instead, the estimated planetary radius would be smaller by 4%, with a  $1\sigma$  uncertainty of 5% in the difference. Note that the planet would be smaller due to its host star being smaller, even though the transits would be somewhat diluted.

Figures 1 and 2 compares the best-fit models to the observations for both HATS-37 and HATS-38. Our final set of adopted stellar parameters derived from this analysis are listed in Table 5, while the adopted planetary parameters are listed in Table 6.

#### 4. DISCUSSION

We put HATS-37Ab and HATS-38b in the context of the population of known, well-characterized<sup>2</sup> transiting exoplanets in Figure 6, where we show a scatter plot of planetary mass versus planetary radius, coding with color the equilibrium temperature. Both planets have a relatively low density close to  $0.3 \text{ g cm}^{-3}$ , which among with their other properties translate into a transmission spectroscopy metric (TSM, Kempton et al. 2018) of  $\approx 120$  for HATS-37Ab and  $\approx 165$  for HATS-38b. The latter figure makes HATS-38b an attractive target among the currently known set of transiting Neptunes for transmission spectroscopy. Both targets populate a region in the mass–radius plane which is sparsely populated and where the transition between gas giants and the population of smaller planets occur. We note that both HATS-37Ab and HATS-38b are among the lowest mass planets found from ground-based wide-field surveys to date, joining a select group of systems uncovered by such surveys with masses  $M_p \lesssim 0.1 M_J$ : HAT-P-26 b ( $0.059 \pm 0.007 M_J$ , Hartman et al. 2011), NGTS-4 b ( $0.0648 \pm 0.0094 M_J$ , West et al. 2019), HAT-P-11 b

<sup>2</sup> We use the catalog of well-characterized planets of Southworth (2011). The catalog is kept updated online at <https://www.astro.keele.ac.uk/jkt/tepcat/> and the data we used were retrieved in November 2019. We restrict the sample to systems whose fractional error on their planetary masses are  $< 50\%$ , and planetary radii are  $< 25\%$ .



**Figure 6.** Mass – Radius diagram for the population of well characterized transiting planets (Southworth 2011). The points corresponding to HATS-37Ab and HATS-38b are indicated with dashed lines. The color represents the equilibrium temperature of the planet, while the size scales down with the transmission spectroscopy metric as defined by Kempton et al. (2018). The dashed gray lines correspond to isodensity curves for 0.3, 3 and 30  $\text{g cm}^{-3}$ , respectively.

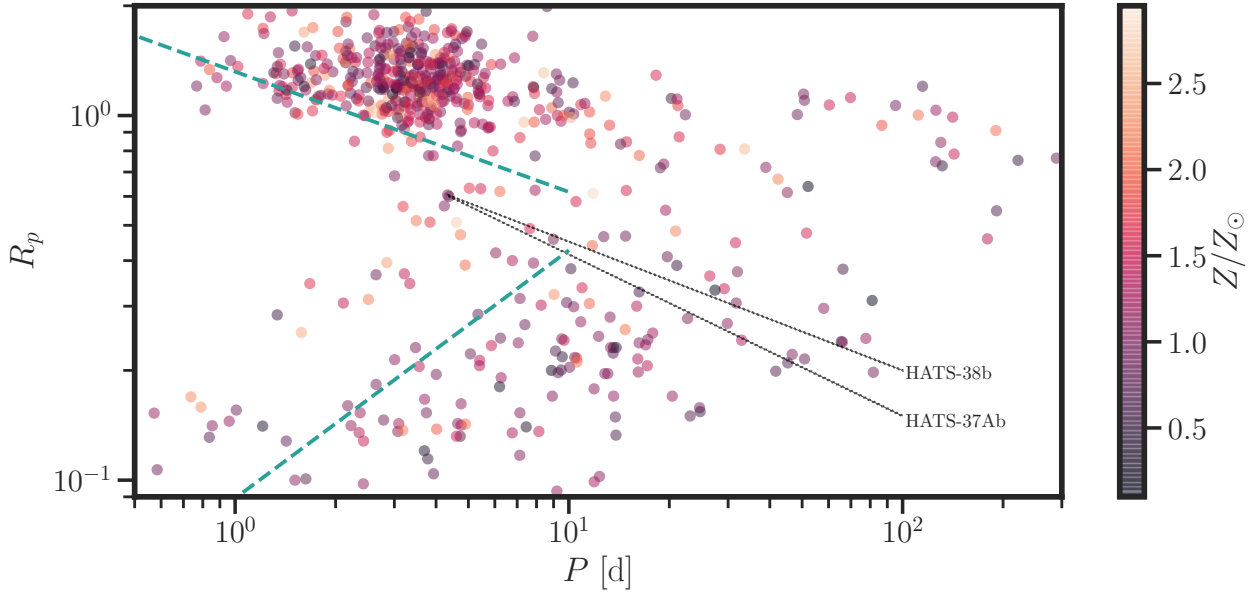
( $0.0736 \pm 0.0047 M_J$ , Bakos et al. 2010; Yee et al. 2018) and WASP-166 b ( $0.101 \pm 0.005 M_J$ , Hellier et al. 2019).

In Figure 7 we show the population of well-characterized planets in the period–radius plane, where HATS-37Ab and HATS-38b are extremely similar. In this figure we show the region defined as the Neptune desert by Mazeh et al. (2016). While not lying in the region with  $P \lesssim 3$  days and  $0.4 \lesssim (R_p/R_J) \lesssim 0.8$  that is essentially devoid of planets, both HATS-37Ab and HATS-38b lie within the region defined as the Neptune desert and that has an intrinsically low occurrence rate of planets.

When we consider additional parameters than planetary mass and radius and consider also the properties of the host stars, the properties of HATS-37Ab and HATS-38b emerge as being particularly rare. Dong et al. (2018) used a large sample of stellar parameters obtained with the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) to further characterize the Neptune desert region. Their study reveals a dearth of planets in the radius range  $6 \lesssim (R_p/R_\oplus) \lesssim 10$ , which they term the Saturn valley, and a population of hot Neptunes with radii  $2 \lesssim (R_p/R_\oplus) \lesssim 6$  which are rare (occurrence rate of  $\approx 1\%$  for FGK stars) and whose occurrence is correlated with metallicity in the sense that hot Neptunes appear preferentially around metal-rich stars. In fact, Dong et al. (2018) find the great majority of the hot Neptunes in their sample to be hosted by stars

with  $[\text{Fe}/\text{H}] \geq 0.1$ . Both HATS-37Ab and HATS-38b have radii  $\approx 6.7 R_\oplus$  making them large specimens for hot Neptunes and veering into the Saturn valley as defined by Dong et al. (2018). More strikingly, HATS-38 has an estimated metallicity of  $\approx -0.1$ , making it a very metal-poor star to host a hot Neptune given the expected occurrence rate at that metallicity of order  $\sim 10^{-3}$  (Dong et al. 2018, see their Figure 4). Even if the metallicity was as high as  $\approx 0.05$ , as allowed at the  $\approx 3.5\sigma$  level, the expected occurrence rate is  $\lesssim 5 \times 10^{-3}$ . Thus, we can see that HATS-37Ab and HATS-38b contribute a new pair of exoplanetary systems with uncommon properties and showcase the continuing contributions of wide-field ground-based surveys to better map the variety of landscapes present in the exoplanetary realm.

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**Figure 7.** Period – Radius diagram for the population of well characterized transiting planets. The point corresponding to HATS-37Ab and HATS-38b are indicated with dotted black lines. The dashed cyan lines mark the boundaries of the Neptune desert as defined by Mazeh et al. (2016). The points are color-coded according to the metallicity of the host star.

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**Table 4.** Astrometric, Spectroscopic and Photometric parameters for HATS-37 and HATS-38

Parameter	HATS-37	HATS-38	Source
	Value	Value	
Astrometric properties and cross-identifications			
2MASS-ID.....	13191246-2259127	10170509-2516345	
GAIA DR2-ID.....	6194574671813047424	5472386851683941376	
TIC-ID.....	6036597	168281028	
R.A. (J2000).....	13 <sup>h</sup> 19 <sup>m</sup> 12.4637 <sup>s</sup>	10 <sup>h</sup> 17 <sup>m</sup> 05.0796 <sup>s</sup>	GAIA DR2
Dec. (J2000).....	-22°59′12.7306″	-25°16′34.5568″	GAIA DR2
$\mu_{R.A.}$ (mas yr <sup>-1</sup> )	-21.78 ± 0.11	-21.752 ± 0.066	GAIA DR2
$\mu_{Dec.}$ (mas yr <sup>-1</sup> )	6.15 ± 0.11	-7.540 ± 0.070	GAIA DR2
parallax (mas)	4.692 ± 0.061	2.883 ± 0.043	GAIA DR2
Spectroscopic properties			
$T_{\text{eff}\star}$ (K).....	5247 ± 50	5740 ± 50	ZASPE <sup>a</sup>
[Fe/H].....	0.040 ± 0.030	0.060 ± 0.026	ZASPE
$v \sin i$ (km s <sup>-1</sup> ).....	3.98 ± 0.30	3.10 ± 0.27	ZASPE
$v_{\text{mac}}$ (km s <sup>-1</sup> ).....	3.175 ± 0.076	3.934 ± 0.076	Assumed
$v_{\text{mic}}$ (km s <sup>-1</sup> ).....	0.818 ± 0.023	1.059 ± 0.028	Assumed
$\gamma_{\text{RV}}$ (m s <sup>-1</sup> ).....	6417 ± 0	4144.0 ± 1.5	HARPS <sup>b</sup>
Photometric properties			
$G$ (mag) <sup>c</sup> .....	11.99780 ± 0.00020	12.27810 ± 0.00020	GAIA DR2
$BP$ (mag) <sup>c</sup> .....	12.5309 ± 0.0023	12.6494 ± 0.0012	GAIA DR2
$RP$ (mag) <sup>c</sup> .....	11.3387 ± 0.0017	11.76070 ± 0.00060	GAIA DR2
$B$ (mag).....	13.222 ± 0.060	13.22 ± 0.11	APASS <sup>d</sup>
$V$ (mag).....	12.266 ± 0.030	12.411 ± 0.030	APASS <sup>d</sup>
$g$ (mag).....	12.733 ± 0.060	12.780 ± 0.037	APASS <sup>d</sup>
$r$ (mag).....	11.906 ± 0.030	12.220 ± 0.057	APASS <sup>d</sup>
$i$ (mag).....	11.616 ± 0.030	12.26 ± 0.19	APASS <sup>d</sup>
$J$ (mag).....	10.528 ± 0.024	11.184 ± 0.026	2MASS
$H$ (mag).....	10.038 ± 0.022	10.850 ± 0.024	2MASS
$K_s$ (mag).....	9.947 ± 0.021	10.768 ± 0.024	2MASS
$W1$ (mag).....	9.866 ± 0.022	10.714 ± 0.023	WISE
$W2$ (mag).....	9.942 ± 0.021	10.783 ± 0.022	WISE
$W3$ (mag).....	9.896 ± 0.047	10.736 ± 0.091	WISE

<sup>a</sup> ZASPE = Zonal Atmospheric Stellar Parameter Estimator routine for the analysis of high-resolution spectra (Brahm et al. 2017b), applied to the FEROS spectra of each system. These parameters rely primarily on ZASPE, but have a small dependence also on the iterative analysis incorporating the isochrone search and global modeling of the data.

<sup>b</sup> The error on  $\gamma_{\text{RV}}$  is determined from the orbital fit to the RV measurements, and does not include the systematic uncertainty in transforming the velocities to the IAU standard system. The velocities have not been corrected for gravitational redshifts.

<sup>c</sup> The listed uncertainties for the Gaia DR2 photometry are taken from the catalog. For the analysis we assume additional systematic uncertainties of 0.002 mag, 0.005 mag and 0.003 mag for the G, BP and RP bands, respectively.

<sup>d</sup> From APASS DR6 as listed in the UCAC 4 catalog (Zacharias et al. 2013).

**Table 5.** Adopted derived stellar parameters for HATS-37 and HATS-38

Parameter	HATS-37 Value	HATS-38 Value
Planet Hosting Star HATS-37A and HATS-38		
$M_*$ ( $M_\odot$ ) .....	$0.843^{+0.017}_{-0.012}$	$0.890^{+0.016}_{-0.012}$
$R_*$ ( $R_\odot$ ) .....	$0.877^{+0.019}_{-0.012}$	$1.105 \pm 0.016$
$\log g_*$ (cgs) .....	$4.478 \pm 0.017$	$4.301 \pm 0.013$
$L_*$ ( $L_\odot$ ) .....	$0.555^{+0.038}_{-0.028}$	$1.179 \pm 0.037$
$T_{\text{eff}*}$ (K) .....	$5326 \pm 44$	$5732 \pm 25$
[Fe/H] .....	$0.051 \pm 0.029$	$-0.102 \pm 0.043$
Age (Gyr) .....	$11.46^{+0.79}_{-1.45}$	$11.89 \pm 0.60$
$A_V$ (mag) .....	$0.258 \pm 0.062$	$0.122 \pm 0.024$
Distance (pc) .....	$211.1 \pm 2.5$	$347.7 \pm 5.1$
Binary Star Companion HATS-37B		
$M_*$ ( $M_\odot$ ) .....	$0.654 \pm 0.033$	...
$R_*$ ( $R_\odot$ ) .....	$0.654 \pm 0.032$	...
$\log g_*$ (cgs) .....	$4.622 \pm 0.023$	...
$L_*$ ( $L_\odot$ ) .....	$0.120 \pm 0.023$	...
$T_{\text{eff}*}$ (K) .....	$4210 \pm 170$	...

NOTE— The listed parameters are those determined through the joint differential evolution Markov Chain analysis described in Section 3. For both systems the RV observations are consistent with a circular orbit, and we assume a fixed circular orbit in generating the parameters listed here. Systematic errors in the bolometric correction tables or stellar evolution models are not included, and likely dominate the error budget.

**Table 6.** Adopted orbital and planetary parameters for HATS-37Ab and HATS-38b

Parameter	HATS-37Ab Value	HATS-38b Value
Light curve parameters		
$P$ (days) .....	$4.3315366 \pm 0.0000041$	$4.375021 \pm 0.000010$
$T_c$ (BJD) <sup>a</sup> .....	$2458006.80145 \pm 0.00050$	$2457725.16042 \pm 0.00072$
$T_{14}$ (days) <sup>a</sup> .....	$0.1214 \pm 0.0010$	$0.1340 \pm 0.0019$
$T_{12} = T_{34}$ (days) <sup>a</sup> .....	$0.00822 \pm 0.00030$	$0.00924 \pm 0.00035$
$a/R_*$ .....	$12.05^{+0.15}_{-0.23}$	$9.81 \pm 0.14$
$\zeta/R_*$ <sup>b</sup> .....	$17.65 \pm 0.25$	$16.02 \pm 0.25$
$R_p/R_*$ .....	$0.0707 \pm 0.0018$	$0.0570 \pm 0.0012$
$b^2$ .....	$0.020^{+0.038}_{-0.017}$	$0.227^{+0.027}_{-0.027}$
$b \equiv a \cos i/R_*$ .....	$0.140^{+0.100}_{-0.092}$	$0.476^{+0.027}_{-0.030}$
$i$ (deg) .....	$89.33 \pm 0.45$	$87.21 \pm 0.18$
HATSouth dilution factors <sup>c</sup>		
Dilution factor 1 .....	$1.000 \pm 0.063$	$0.964 \pm 0.036$
Dilution factor 2 .....	...	$0.90 \pm 0.10$
Limb-darkening coefficients <sup>d</sup>		
$c_1, r$ .....	0.5594	$0.23 \pm 0.13$
$c_2, r$ .....	0.1497	$0.35 \pm 0.16$
$c_1, R$ .....	0.5328	...
$c_2, R$ .....	0.1491	...
$c_1, i$ .....	0.4491	$0.37^{+0.11}_{-0.14}$
$c_2, i$ .....	0.1683	$0.34 \pm 0.15$
RV parameters		
$K$ ( $\text{m s}^{-1}$ ) .....	$13.9 \pm 5.8$	$9.9 \pm 1.5$
$\gamma$ ( $\text{m s}^{-1}$ ) .....	$6417 \pm 0$	$4144.0 \pm 1.5$
$\dot{\gamma}$ ( $\text{m s}^{-1} \text{d}^{-1}$ ) .....	$0.4539 \pm 0.0015$	...
$e$ <sup>e</sup> .....	$< 0.345$	$< 0.122$
RV jitter FEROS ( $\text{m s}^{-1}$ ) <sup>f</sup> ..	...	$15.3 \pm 5.3$
RV jitter HARPS ( $\text{m s}^{-1}$ ) ...	$< 72.8$	$< 2.4$
RV jitter PFS ( $\text{m s}^{-1}$ ) .....	$8.0 \pm 3.0$	$< 5.4$
Planetary parameters		
$M_p$ ( $M_J$ ) .....	$0.099 \pm 0.042$	$0.074 \pm 0.011$
$R_p$ ( $R_J$ ) .....	$0.606 \pm 0.016$	$0.614 \pm 0.017$
$C(M_p, R_p)$ <sup>g</sup> .....	0.03	-0.06
$\rho_p$ ( $\text{g cm}^{-3}$ ) .....	$0.55 \pm 0.24$	$0.403 \pm 0.071$
$\log g_p$ (cgs) .....	$2.83 \pm 0.19$	$2.691 \pm 0.075$
$a$ (AU) .....	$0.04913^{+0.00033}_{-0.00023}$	$0.05036^{+0.00030}_{-0.00023}$
$T_{\text{eq}}$ (K) .....	$1085^{+16}_{-12}$	$1294 \pm 10$
$\Theta$ <sup>h</sup> .....	$0.0190 \pm 0.0080$	$0.0136 \pm 0.0022$
$\log_{10}(F)$ (cgs) <sup>i</sup> .....	$8.495^{+0.026}_{-0.020}$	$8.801 \pm 0.014$

Table 6 continued

Table 6 (continued)

Parameter	HATS-37Ab Value	HATS-38b Value
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NOTE.— For all systems we adopt a model in which the orbit is assumed to be circular. See the discussion in Section 3.

- <sup>a</sup> Times are in Barycentric Julian Date calculated directly from UTC *without* correction for leap seconds.  $T_c$ : Reference epoch of mid transit that minimizes the correlation with the orbital period.  $T_{12}$ : total transit duration, time between first to last contact;  $T_{12} = T_{34}$ : ingress/egress time, time between first and second, or third and fourth contact.
- <sup>b</sup> Reciprocal of the half duration of the transit used as a jump parameter in our MCMC analysis in place of  $a/R_*$ . It is related to  $a/R_*$  by the expression  $\zeta/R_* = a/R_*(2\pi(1 + e \sin \omega))/(P\sqrt{1 - b^2}\sqrt{1 - e^2})$  (Bakos et al. 2010).
- <sup>c</sup> Scaling factor applied to the model transit that is fit to the HATSouth light curves. This factor accounts for dilution of the transit due to blending from neighboring stars and over-filtering of the light curve. These factors are varied in the fit, with independent values adopted for each HATSouth light curve. The factor listed for HATS-37 is for the G567.1 light curve, while for HATS-38 we list the factors for the G561.1, and G561.1.focus light curves in order.
- <sup>d</sup> Values for a quadratic law. For HATS-37 the values were determined from the tabulations of Claret (2004) for values of the stellar atmospheric parameters, which varied in the modelling. We list here the values for the spectroscopically determined atmospheric parameters. For HATS-38, the limb darkening parameters were directly varied in the fit, using the tabulations from Claret et al. (2012, 2013); Claret (2018) to place prior constraints on their values. The difference in treatment between the two systems stems from differences in the software used to model the blended system HATS-37 and the unblended system HATS-38.
- <sup>e</sup> The 95% confidence upper limit on the eccentricity determined when  $\sqrt{e} \cos \omega$  and  $\sqrt{e} \sin \omega$  are allowed to vary in the fit.
- <sup>f</sup> Term added in quadrature to the formal RV uncertainties for each instrument. This is treated as a free parameter in the fitting routine. In cases where the jitter is consistent with zero, we list its 95% confidence upper limit.
- <sup>g</sup> Correlation coefficient between the planetary mass  $M_p$  and radius  $R_p$  estimated from the posterior parameter distribution.
- <sup>h</sup> The Saffronov number is given by  $\Theta = \frac{1}{2} (V_{\text{esc}}/V_{\text{orb}})^2 = (a/R_p)(M_p/M_*)$  (see Hansen & Barman 2007).
- <sup>i</sup> Incoming flux per unit surface area, averaged over the orbit.

**Table 7.** Relative radial velocities and bisector spans for HATS-37 and HATS-38.

System	BJD (2,450,000+)	RV <sup>a</sup> (m s <sup>-1</sup> )	$\sigma_{RV}$ <sup>b</sup> (m s <sup>-1</sup> )	BS (m s <sup>-1</sup> )	$\sigma_{BS}$ (m s <sup>-1</sup> )	Phase	Instrument
<b>HATS-37</b>							
HATS-37	7505.50363	-43.39	15.00	83.0	19.0	0.268	HARPS
HATS-37	7507.79700	32.57	12.00	108.0	16.0	0.797	HARPS
HATS-37	7557.51991	0.29	2.71	31.5	10.7	0.277	PFS
HATS-37	7559.58237	...	...	15.2	8.4	0.753	PFS
HATS-37	7559.61286	12.06	3.25	0.0	11.2	0.760	PFS
HATS-37	7614.48266	0.50	4.95	32.2	17.6	0.427	PFS
HATS-37	7615.48351	4.63	4.11	3.8	10.5	0.658	PFS
HATS-37	7617.48123	-5.21	3.30	-36.9	10.0	0.120	PFS
HATS-37	7619.48263	18.92	7.62	-107.5	33.0	0.582	PFS
HATS-37	7622.48860	-15.30	3.16	27.1	11.4	0.276	PFS
HATS-37	7623.47962	-7.39	3.12	10.3	11.8	0.504	PFS
HATS-37	7624.49150	6.33	4.59	36.5	13.4	0.738	PFS
HATS-37	7849.68766	25.22	4.06	-52.0	10.3	0.728	PFS
HATS-37	7858.79784	-0.39	4.54	-130.3	16.1	0.831	PFS
<b>HATS-38</b>							
HATS-38	7708.80458	-23.72	7.70	18.0	10.0	0.262	HARPS
HATS-38	7736.74573	9.76	8.60	-43.0	13.0	0.648	FEROS
HATS-38	7737.84703	-0.54	8.20	-17.0	12.0	0.900	FEROS
HATS-38	7740.84458	-8.94	9.70	38.0	14.0	0.585	FEROS
HATS-38	7741.83263	20.76	7.90	-7.0	12.0	0.811	FEROS
HATS-38	7759.79504	50.26	9.00	-29.0	13.0	0.917	FEROS
HATS-38	7804.60303	-6.22	8.40	-7.0	11.0	0.158	HARPS
HATS-38	7805.54338	-8.04	10.10	35.0	14.0	0.373	FEROS
HATS-38	7805.60189	-20.22	6.60	-11.0	9.0	0.387	HARPS
HATS-38	7806.61869	-1.12	8.40	15.0	11.0	0.619	HARPS
HATS-38	7806.78686	5.26	12.10	8.0	17.0	0.658	FEROS
HATS-38	7807.54628	-21.74	13.50	125.0	18.0	0.831	FEROS
HATS-38	7829.55448	7.86	8.80	-27.0	13.0	0.862	FEROS
HATS-38	7830.69385	-10.24	8.50	12.0	13.0	0.122	FEROS
HATS-38	7848.60266	-18.23	3.02	-0.5	14.9	0.215	PFS
HATS-38	7849.55287	-1.57	3.11	12.9	19.6	0.433	PFS
HATS-38	7850.56508	5.85	3.02	-3.7	11.4	0.664	PFS
HATS-38	7851.62685	11.30	3.89	-25.4	40.4	0.907	PFS
HATS-38	7862.63029	...	...	9.0	10.3	0.422	PFS
HATS-38	7866.48140	-6.92	3.90	10.0	5.0	0.302	HARPS
HATS-38	7866.52106	-14.82	4.40	0.0	6.0	0.311	HARPS
HATS-38	7867.48250	1.88	5.80	1.0	7.0	0.531	HARPS
HATS-38	7867.50397	-1.52	6.70	-5.0	9.0	0.536	HARPS
HATS-38	7868.49777	-6.32	7.70	0.0	10.0	0.763	HARPS
HATS-38	7868.52092	2.58	7.80	-9.0	10.0	0.768	HARPS
HATS-38	7870.52143	-1.52	4.40	-3.0	6.0	0.225	HARPS
HATS-38	7870.54312	-9.22	4.40	-1.0	6.0	0.230	HARPS
HATS-38	7871.52764	0.18	3.90	1.0	5.0	0.455	HARPS
HATS-38	7871.54726	-0.32	4.40	-3.0	6.0	0.460	HARPS
HATS-38	7887.50781	-35.12	13.40	5.0	18.0	0.108	HARPS
HATS-38	7887.53008	-14.52	15.00	5.0	20.0	0.113	HARPS
HATS-38	7890.47840	10.18	7.80	-4.0	10.0	0.787	HARPS
HATS-38	7890.50175	9.78	8.40	-1.0	11.0	0.792	HARPS

<sup>a</sup> The zero-point of these velocities is arbitrary. An overall offset  $\gamma_{rel}$  fitted independently to the velocities from each instrument has been subtracted.