Three Short Period Jupiters from TESS

HIP 65Ab, TOI-157b and TOI-169b

L. D. Nielsen1, R. Brah1, F. Bouch1, N. Espinoza1, O. Turner, S. Rappaport5, L. Pearce6, G. Ricker5, R. Vanderspek5, D.W. Latham7, S. Seager6, J.N. Winn10, J.M. Jenkins11, J.S. Acton12, G. Bakos10, T. Barclay13, K. Barbakau1, W. Bhatti10, C. Briceño17, E.M. Bryant18, 19, M.R. Burleigh12, D.R. Ciardi20, K.A. Collins9, K.I. Collins21, B.F. Cooke18, Z. Csubry10, L.A. dos Santos1, Ph. Eigmüller22, M. M. Fausnaugh5, T. Gan23, M. Gillon15, M.R. Goad12, N. Guerrero5, J. Hagelberg1, R. Hart24, T. Henning25, C.X. Huang5, E. Jehin26, J.S. Jenkins27, A. Jordán2, J.F. Kielkopf20, D. Kossakowski25, B. Lavie1, N. Law30, M. Lendl31, J.P. de Leon32, C. Lovis1, A.W. Mann30, M. Marmier18, 19, M. Mor132, M. Moya29, N. Narita34, 35, 36, 37, D. Ospí38, J.F. Otegí1, 19, F. Pepe1, F.J. Pozuelos25, 15, L. Raynard12, H.M. Relles7, P. Sarkis25, D. Ségransan1, J.V. Seidel1, A. Shporer1, M. Stalport1, C. Stockdale50, V. Suc2, M. Tamura32, 34, 36, T.G. Tan3, R.H. Tilbrook12, E.B. Ting11, T. Trifonov25, S. Udry1, A. Vanderburg42, P.J. Wheatley18, 19, G. Wingham43, Z. Zhan4, Z. and C. Ziegler44

(Affiliations can be found after the references)

Received nnn; accepted nnn.

ABSTRACT

We report the confirmation and mass determination of three hot Jupiters discovered by the Transiting Exoplanet Survey Satellite (TESS) mission: HIP 65Ab (TOI-129, TIC 201248411) is an ultra-short-period Jupiter orbiting a bright (V = 11.1 mag) K4-dwarf every 0.98 days. It is a massive 3.213 ± 0.078 M Jupiter in a grazing transit configuration with impact parameter b = 1.17 ± 0.10. As a result the radius is poorly constrained, 2.03 ± 0.61 R J. We perform a full phase-curve analysis of the TESS data and detect both illumination- and ellipsoidal variations as well as Doppler boosting. HIP 65A is part of a binary stellar system, with HIP 65B separated by 269 AU (3.95 arcsec on sky). TOI-157b (TIC 140691463) is a typical hot Jupiter with a mass 1.18 ± 0.13 M J and radius 1.29 ± 0.02 R J. It has a period of 2.08 days, which corresponds to a separation of just 0.03 AU. This makes TOI-157 an interesting system, as the host star is an evolved G9 sub-giant star (V = 11.1 mag) K4-dwarf every 0.98 days. It is a massive 3.213 ± 0.078 M J. We find an occurrence rate of 0.40 ± 0.10% which is in agreement with statistics based on the Kepler mission (Fressin et al. 2013; Santerne et al. 2016). An even rarer sub-population of hot Jupiters are the ultra-short-period (USP) Jupiters with orbital periods shorter than 1 day. To date only 8 such planets are known; WASP-18b (Hellier et al. 2010); WASP-43b (Hellier et al. 2011); WASP-103b (Gillon et al. 2014); HAT-S-18b (Penev et al. 2016); KELT-16b (Oberst et al. 2017); NGTS-6b (Vines et al. 2019) and NGTS-10b (McCormac et al. 2020). Hot Jupiters, and in particular USP Jupiters, can offer insights into planet-star interactions such as photo-evaporation and atmospheric escape (Bourrier et al. 2020; Owen & Lai 2018; Murray-Clay et al. 2009), atmospheric structure and chemistry (Parmentier et al. 2018; Kataria et al. 2015; Kreidberg et al. 2014; Murgas et al. 2014) and tidal decay (Yee et al. 2020). These planets shape the upper edge of the Neptune desert (Mazeh et al. 2016; Szabó & Kiss 2011) which constitutes a dearth of sub-Jovian planets at short periods. The proposed

1. Introduction

The Transiting Exoplanet Survey Satellite (TESS - Ricker et al. 2015) has since July 2018 surveyed the Southern and Northern hemispheres for exoplanets transiting bright stars. Based on the first year of observations in the south (Sectors 1 - 13) a total number of 1117 TESS Objects-of-Interest (TOIs) (Guerrero et al. submitted) have been identified. Currently, 667 of these are still considered as planet candidates and 55 have been confirmed as new TESS-planets and 4 as transiting brown dwarfs (including studies in preparation and published results, see eg. Cañas et al. 2019; Jones et al. 2019; Esposito et al. 2019; Günther et al. 2019; Eisner et al. 2020; Díaz et al. 2020; Nielsen et al. 2020; Šubjak et al. 2019; Carmichael et al. 2020). 146 of the TOIs from Sectors 1 - 13 are previously known planets.

A recent study by Zhou et al. 2019 offers a first estimate of the occurrence rate of hot Jupiters discovered by TESS by analysing a sample of bright (T mag < 10) main sequence stars observed by TESS. They find an occurrence rate of 0.40 ± 0.10% which is in agreement with statistics based on the Kepler mission (Fressin et al. 2013; Santerne et al. 2016). An even rarer sub-population of hot Jupiters are the ultra-short-period (USP) Jupiters with orbital periods shorter than 1 day. To date only 8 such planets are known; WASP-18b (Hellier et al. 2009); WASP-19b (Hebb et al. 2010); WASP-43b (Hellier et al. 2011); WASP-103b (Gillon et al. 2014); HAT-S-18b (Penev et al. 2016); KELT-16b (Oberst et al. 2017); NGTS-6b (Vines et al. 2019) and NGTS-10b (McCormac et al. 2020).
mechanisms creating the desert are numerous, but can generally be regarded as a combination of three dominant processes; photo-evaporation stripping less massive planets of their outer layers (Lundkvist et al. 2016; Owen & Lai 2018), availability of disk material during planet formation (Armitage 2007) and planet migration (Demangeon et al. 2018; Alexander & Armitage 2009).

Massive close-in planets also challenge current planet formation models; they represent the bulk of the mass and angular momentum in their systems while shaping their formation and evolution over time. An extreme case is NGTS 1b, a hot Jupiter around a M0 star (Bayliss et al. 2018). Both in-situ formation and scenarios where the Jupiter is formed far out in the system followed by subsequent inward migration are still being considered in order to explain the presence of hot Jupiters (Bailey & Batygin 2018; Nagasawa et al. 2008).

In this work, we present one USP and two hot Jupiters orbiting bright stars observed by TESS in its first year of operation. Table 1 lists the host stars stellar parameters. We model the systems self consistently with EXOFastV2 using transit light curves and radial velocity (RV) measurements to obtain masses and radii for all three systems. Our analysis is based on radial velocity data from the high resolution spectrographs CORALIE on the Swiss 1.2 m telescope and FEROS on the 2.2 m MPG/ESO telescope, both in La Silla, Chile. In addition to the TESS data, we also utilise data from ground based photometric facilities that are part of the TESS Follow-Up Observing Program; LCOGT, NGTS, CHAT, Trappist-South, IRSF, PEST, Mt. Stuart Observatory, MKO and Hazelwood Observatory. SOAR speckle imaging is used to rule out close stellar companions.

2. Observations

A summary of all the data used in the joint analysis of HIP 65A, TOI-157b and TOI-169b can be found in Table 2. Additionally SOAR speckle imaging was used to rule out close stellar companions, as described in Sec. 2.4.

2.1. Discovery photometry from TESS

HIP 65A, TOI-157 and TOI-169 were all observed by TESS in multiple Sectors and announced as TOIs from Sector 1 by the TESS Science Office. HIP 65A (TIC 129, TIC 201248411) was observed with 2-min cadence in Sectors 1 and 2 from 2018-Jul-25 to 2018-Sep-20. TOI-157 (TIC 140691463) was observed in Sectors 1-8 in the full frame images (FFI) with 30-min cadence and in Sectors 9, 11, 12 and 13 with 2-min cadence. TOI-169 was observed in the FFIs in Sector 1 and later in Sector 13 with 2-min cadence.

For the Sectors with 2-min data available we use the publicly available Simple Aperture Photometry flux with Pre-search Data Conditioning (PDC-SAP) (Stumpe et al. 2014, 2012; Smith et al. 2012; Jenkins et al. 2010) provided by the Science Processing Operations Center (SPOC - Jenkins et al. 2016). For the FFI data we utilised light curves produced by the MIT Quick Look pipe-line (QLP, Huang et al. in prep.).

2.2. Follow-up spectroscopy with CORALIE & FEROS

HIP 65A, TOI-157 and TOI-169 were observed with the high resolution spectrograph CORALIE on the Swiss 1.2 m Euler telescope at La Silla Observatory (Queloz et al. 2001b). CORALIE is fed by a 2′′ fibre and has a resolution of $R = 60,000$. Radial velocities (RVs) and line bisector spans were calculated via cross-correlation with a G2 binary mask, using the standard CORALIE data-reduction pipeline.

The three systems were also monitored with the FEROS spectrograph (Kaufer & Pasquini 1998) mounted on the MPG 2.2m telescope installed at La Silla Observatory. FEROS has a spectral resolution of $R = 48,000$ and is fibre fed from the telescope. Observations were performed with the simultaneous calibration mode where a second fibre is illuminated by a Thorium-Argon lamp in order to trace the instrumental radial velocity drift. 17, 2, and 10 FEROS spectra were obtained for HIP 65A, TOI-157 and TOI-169, respectively. FEROS data were processed with the CERES pipeline (Brahm et al. 2017), which delivers precision radial velocities computed via the cross-correlation technique.

The first few RV measurements were used for recognition, to check for a visual or spectroscopic binary. Once a significant change in RV had been identified to be consistent with the ephemerides provided by TESS we commenced intensive follow-up observations. The RVs from both CORALIE and FEROS are listed in Appendix A (online version only). In Figs. 8, 10 and 12 we plot the RV time series along with our best-fit from the joint analysis (Sec. 4).

To ensure that the RV signal does not originate from cool stellar spots or a blended eclipsing binary, we checked for correlations between the line bisector span and the RV measurements (Queloz et al. 2001a). We found no evidence for correlation for any of our targets.

2.3. Follow-up photometry

We acquired ground-based time-series follow-up photometry of HIP 65A, TOI-157 and TOI-169 as part of the TESS Follow-Up Observing Program (TFOP) to attempt to (1) rule out nearby eclipsing binaries (NEBs) as potential sources of the TESS detection, (2) detect the transit-like event on target to confirm the event depth and thus the TESS photometric deblending factor, (3) refine the TESS ephemerides, (4) provide additional epochs of transit centre time measurements to supplement the transit timing variation (TTV) analysis, and (5) place constraints on transit depth differences across optical filter bands. We used the TESS Transit Finder, which is a customised version of the Tapir software package (Jensen 2013), to schedule our transit observations.

2.3.1. Las Cumbres Observatory Global Telescope (LCOGT)

Five, four, and three full transits of HIP 65A, TOI-157 and TOI-169, respectively, were observed using the Las Cumbres Observatory Global Telescope (LCOGT) 1.0-m and 0.4-m network (Brown et al. 2013) nodes at Cerro Tololo Inter-American Observatory (CTIO), Siding Spring Observatory (SSO), and South Africa Astronomical Observatory (SAAO). The 1.0-m telescopes are equipped with 4096 × 4096 LCO SINISTRO cameras having an image scale of 0.′′389 pixel$^{-1}$ resulting in a 26′ × 26′ field of view. The 0.4-m telescopes are equipped with 2048 × 3072 SBIG STX6303 cameras having an image scale of 0′′.57 pixel$^{-1}$ resulting in a 19′ × 29′ field of view. The images were calibrated using the standard LCOGT BANZAI pipeline (McCully et al. 2018). The photometric data were extracted using the AstroImageJ (AIJ) software package (Collins et al. 2017).
Two full transits of HIP 65Ab were observed using the Next Generation Transit Survey (NGTS) telescope guiding performed by the DONUTS algorithm (Mc Cormac et al. 2013). The data reduction was performed using a custom aperture photometry pipeline. For the reduction, comparison stars, which were similar to HIP 65A in both apparent magnitude and colour, were automatically selected.

2.3.3. Chilean-Hungarian Automated Telescope (CHAT)

A full transit of TOI-169 was obtained with the 0.7 m Chilean-Hungarian Automated Telescope (CHAT) installed at Las Campanas Observatory in Chile. The observations took place on the night of 2018-Oct-01, using the sloan i filter and an exposure time of 130 s. The 60 science images where processed with a sub-pixel level stability of the target on the CCD, thanks to the telescope guiding performed by the DONUTS algorithm (Mc Cormac et al. 2013). The data reduction was performed using a custom aperture photometry pipeline. For the reduction, comparison stars, which were similar to HIP 65A in both apparent magnitude and colour, were automatically selected.

2.3.2. Next Generation Transit Survey (NGTS)

Two full transits of HIP 65Ab were observed using the Next Generation Transit Survey (NGTS Wheatley et al. 2018) on the nights UT 2018-Nov-30 and 2018-Dec-02. On both nights, a single 0.2 m NGTS telescope was used. Across the two nights, a total of 2422 images were obtained using the custom NGTS filter (520 - 890 nm) and an exposure time of 10 seconds. We had sub-pixel level stability of the target on the CCD, thanks to the telescope guiding performed by the DONUTS algorithm (Mc Cormac et al. 2013). The data reduction was performed using a custom aperture photometry pipeline. For the reduction, comparison stars, which were similar to HIP 65A in both apparent magnitude and colour, were automatically selected.

Table 1. Stellar Properties for HIP 65A, TOI-157 and TOI-169. Results for stellar parameters modelled in this study can be found in Table 5.

| Property               | HIP 65A | TOI-157 | TOI-169 | Source              |
|------------------------|---------|---------|---------|---------------------|
| Spectral type          | K4V     | G9IV    | GTV     | Pecaut & Mamajek (2013) |
| 2MASS ID               | J000044490-5449498 | J04544830-7640498 | J01070679-7511559 | 2MASS |
| Gaia DR2               | 4923860051276772608 | 46249799393181971328 | 468453614202233728 | Gaia |
| TIC ID                 | 2012484111 | 140691463 | 183120439 | TESS |
| TOI                    | TOI-129 | TOI-157 | TOI-169 | TESS |

Notes. Tycho (Høg et al. 2000); 2MASS (Skrutskie et al. 2006); WISE (Wright et al. 2010); Gaia (Gaia Collaboration et al. 2018); APASS (Henden & Munari 2014). Spectral type is based on T\textsubscript{eff} from global modeling (see Section 4) and Table 5 in Pecaut & Mamajek (2013).
Table 2. Summary of the discovery TESS-photometry, follow-up photometry and radial velocity observations of HIP 65A, TOI-157 and TOI-169.

| Date            | Source          | N.Obs / Filter |
|-----------------|-----------------|----------------|
| **HIP 65A (TOI-129)** |                 |                |
| 2018 July – Sep | TESS 2 min      | TESS           |
| 2018 Nov – Dec  | CORALIE         | 17             |
| 2018 Nov – Dec  | FEROS           | 17             |
| 2018 Sep 7     | LCO-SSO         |                 |
| 2018 Sep 10    | MKO             |                 |
| 2018 Sep 13    | LCO-SSO         | B              |
| 2018 Sep 13    | LCO-SSO         |                 |
| 2018 Sep 14    | LCO-SSO         | B              |
| 2018 Sep 14    | LCO-SSO         |                 |
| 2018 Sep 14    | PEST            | V              |
| 2018 Nov 30    | NGTS            | NGTS           |
| 2018 Dec 2     | NGTS            | NGTS           |
| **TOI-157**    |                 |                |
| 2018 July – 2019 Feb | TESS FFI      | TESS           |
| 2018 Mar – July | TESS 2 min      | TESS           |
| 2018 Nov – 2019 Jan | CORALIE   | 24             |
| 2018 Nov – Dec  | FEROS           | 2              |
| 2018 Sep 15    | LCO-SAAO        |                 |
| 2018 Sep 21    | LCO-CTIO 0.4 m  |                 |
| 2018 Oct 07    | IRSF            | H              |
| 2018 Oct 07    | IRSF            | J              |
| 2018 Oct 18    | MtStuart        | g              |
| 2018 Oct 22    | Hazelwood       | ic             |
| 2018 Oct 24    | Hazelwood       | ic             |
| 2018 Nov 08    | LCO-CTIO        | g              |
| 2018 Nov 08    | LCO-CTIO        |                 |
| **TOI-169**    |                 |                |
| 2018 July 25 – Sep 20 | TESS FFI  | TESS           |
| 2019 Jun – Jul  | TESS 2 min      | TESS           |
| 2018 Oct – Nov  | FEROS           | 10             |
| 2019 Jun – Jul  | CORALIE         | 6              |
| 2018 Sep 11    | LCO-SAAO        |                 |
| 2018 Sep 26    | LCO-SAAO        |                 |
| 2018 Oct 01    | CHAT            |                 |
| 2018 Nov 03    | Trappist-South  | B              |
| 2018 Nov 13    | LCO-CTIO        | g              |

2.3.4. TRAPPIST-South

TRAPPIST-South at ESO-La Silla Observatory in Chile is a 60 cm Ritchey-Chretien telescope, which has a thermoelectrically cooled 2K × 2K FLI Proline CCD camera with a field of view of 22′ × 22′ and pixel-scale of 0.65 arcsec pixel−1 (for more detail, see Jehin et al. 2011; Gillon et al. 2013). We carried out a full-transit observation of TOI-169 on 2018-Nov-03 with B filter with an exposure time of 50 s. We took 220 images and made use of AJ to perform aperture photometry. The optimum aperture being 7 pixels (4.′55) and a PSF of 2.′80. We confirmed the event on the target star and we cleared all the stars of eclipsing binaries within 2.5 arcmin around the target star.

2.3.5. Infrared Survey Facility (IRSF)

TOI-157 was observed with the Infrared Survey Facility (IRSF) 1.4 m telescope located in Sutherland, South Africa on UT 2018- Oct-7. We used the Simultaneous Infrared Imager for Unbiased Survey (SIRIUS: Nagayama et al. 2003) camera for the observation, which is equipped with two dichroic mirrors and can take J, H, and Ks bands simultaneously with three 1K×1K HgCdTe detectors. On the observing night, the Ks band detector had a trouble, and only J and H band data were useful. We took 300 frames for each band with an exposure time of 60 seconds. We used a position locking software introduced in Narita et al. (2013) during the observation. We applied a dedicated pipeline for the SIRIUS data1 to make sky flats. Dark subtraction, flat fielding, and subsequent standard aperture photometry were done with a customised pipeline by Fukui et al. (2011).

2.3.6. Perth Exoplanet Survey Telescope (PEST)

We observed a full transit of HIP 65Ab on UTC 2018-Sep-14 in V-band from the Perth Exoplanet Survey Telescope (PEST) near Perth, Australia. The 0.3 m telescope is equipped with a 1530 × 1020 SBIG ST-8XM3 camera with an image scale of 1.′2 pixel−1 resulting in a 31′ × 21′ field of view. A custom pipeline based on C-munipack2 was used to calibrate the images and extract the differential photometry, using an aperture with radius 10′6. The images have typical stellar point spread functions (PSFs) with a FWHM of ~ 4′.

2.3.7. Mt. Stuart Observatory

We observed a full transit of TOI-157 on UTC 2018-Oct-18 in g′-band from Mt. Stuart near Dunedin, New Zealand. The 0.32 m telescope is equipped with a 3072 × 2048 SBIG STL6303E camera with an image scale of 0′88 pixel−1 resulting in a 44′ × 30′ field of view. AJ was used to calibrate the images and extract the differential photometry with an 8′8 aperture radius. The images have typical stellar PSFs with a FWHM of ~ 5′.

2.3.8. Mt. Kent Observatory (MKO)

We observed a full transit of HIP 65Ab on UTC 2018-Sep-10 in r′-band from Mt. Kent Observatory (MKO) near Toowoomba, Australia. The 0.7-m telescope is equipped with a 4096 × 4096 Apogee Alta F16 camera with an image scale of 0′.41 pixel−1 resulting in a 27′ × 27′ field of view. AJ was used to calibrate the images and extract the differential photometry with a 3′3 aperture radius. The images have typical stellar PSFs with a FWHM of ~ 2′.

2.3.9. Hazelwood Observatory

Hazelwood Observatory is a backyard observatory located in Victoria, Australia. Photometric follow-up data for TOI-157 was obtained on 2018-Oct-22 and 24 in the ic band, using a 0.32-m Planewave CDK telescope and SBIG STT3200 CCD camera, with 2148 × 1472 pixels (FoV 20′ × 13′). The observations on 2018-Oct-22 covered a full transit with some observations missing near ingress and at mid-transit due to passing cirrus cloud. The observations taken on 2018-Oct-24 were not continuous due to passing cirrus cloud. The frames were corrected for Bias, Dark and Flat Fields using MaximDL. Differential photometry was extracted using AJ.

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1 http://irsf-software.appspot.com/yas/nakajima/sirius.html
2 http://c-munipack.sourceforge.net
2.4. SOAR speckle imaging

TESS is in-sensitive to close companions due to its relatively large 21" pixels. Companion stars can contaminate the photometry, resulting in an underestimated planetary radius or may be the source of an astrophysical false positive. We searched for previously unknown companions to HIP 65A, TOI-157 and TOI-169 with SOAR speckle imaging (Tokovinin 2018) on UT 2018-Sep-25 and UT 2018-Oct-21, observing in a similar visible band-pass as TESS. Further details of the observations are available in Ziegler et al. (2019). We did not detect any nearby stars to the three host stars within 3". The 5σ detection sensitivity and the speckle auto-correlation function from the SOAR observations are plotted in Fig. 1.

3. Spectral analysis

Stellar atmospheric parameters, including effective temperature, \( T_{\text{eff}} \), surface gravity, \( \log g \), and metallicity, \( [\text{Fe}/\text{H}] \), were derived using SpecMatch-emp (Yee et al. 2017) on stacked FEROS spectra for HIP 65A and TOI-169. For TOI-157, we ran SpecMatch-emp on stacked CORALIE spectra.

SpecMatch-emp matches the input spectra to a vast library of stars with well-determined parameters derived with a variety of independent methods, e.g., interferometry, optical and NIR photometry, asteroseismology, and LTE analysis of high-resolution optical spectra. We used the spectral region around the Mg I b triplet (5100 - 5340 Å) to match our spectrum to the library spectra through \( \chi^2 \) minimisation. A weighted linear combination of the five best matching spectra were used to extract \( T_{\text{eff}} \), \( R_\star \) and \( [\text{Fe}/\text{H}] \).

The projected rotational velocity of the star, \( v \sin i \), was computed using the calibration between \( v \sin i \) and the width of the CORALIE CCF from Santos et al. (2002). The formal result was smaller than what can be resolved by CORALIE, and we can therefore only establish an upper limit of 2.5 km s\(^{-1}\).

4. Joint analysis of transit light curves and RVs

The planetary and stellar parameters for the three systems were modelled jointly and self-consistently using the TESS discovery light curves, followup photometry and radial velocity measurements from FEROS and CORALIE. We use the most recent version of EXOFASTv2 (Eastman et al. 2019, 2013), which can fit any number of transits and RV sources while exploring the vast parameter space through a differential evolution Markov Chain coupled with a Metropolis-Hastings Monte Carlo sampler. Built-in Gelman-Rubin statistic (Gelman & Rubin 1992; Gelman et al. 2003; Ford 2006) is used to check the convergence of the chains. We ran EXOFASTv2 until convergence, and discarded the first chains which have \( \chi^2 \) above the median \( \chi^2 \) as the ‘burn-in’ phase, not to bias the final posterior distributions toward the starting point.

At each step in the MCMC, we evaluate the stellar properties and limb darkening coefficients by interpolating tables from Claret & Bloemen (2011). The analytic expressions from Mandel & Agol (2002) are used for the transit model and a standard single Keplerian orbit for the RV signal. Four parameters are fitted for the star \( T_{\text{eff}}, [\text{Fe}/\text{H}], \log M \), and \( R_\star \). We applied Gaussian priors on \( T_{\text{eff}} \) and \( [\text{Fe}/\text{H}] \) from the spectral analysis, presented in Sec. 3. Stellar density is determined from the transit light curve. The Gaia DR2 parallax was used along with SED-fitting of the broad band photometry presented in Table 1 to constrain the stellar radius further. We set an upper limit on the V-band extinction from Schlegel et al. (1998) and Schlafly & Finkbeiner (2011), to account for reddening along the line of sight. Combining all this information allows us to perform detailed modelling of the star with the Mesa Isochrones and Stellar Tracks (MIST Dotter 2016; Choi et al. 2016).

When modelling RVs and transit photometry simultaneously, each planet has five free parameters (assuming a circular orbit) and two additional RV terms for each instrument (CORALIE &
We denoted them HIP 65A and HIP 65B. Their angular separation on sky corresponds to 245 AU. HIP 65B is a M-dwarf with $T_{\text{eff}} = 3713^{+964}_{-280}$ K according to Gaia DR2. The work by Anders et al. (2019) presents more detailed modelling of Gaia stars including HIP 65B. They present a refined effective temperature of 3861$^{+15}$K and mass of 0.30$^{+0.03}_{-0.05}$M$_\odot$. Table 3 summarises the fundamental properties of HIP 65B.

The blending effect from the HIP 65B star was not taken into account when producing the PDC-SAP light curve, as the star was not included in the TESS input catalog version 7 (TICv7, Stassun et al. 2018) which was used to correct the normalised light curve for dilution. TICv8 (Stassun et al. 2019) does include HIP 65B which has $T = 14.30$ mag, which means it is fainter than HIP 65A by $\Delta T = 4.4$ mag. The effect of dilution is small, but non-negligible. Therefore we fit dilution parameters for this target in all photometric bands, assuming all follow-up light curves include light from both stars. For the TESS band we use the TESS magnitude to compute the dilution factor. For the photometric bands in which the follow-up light curves were taken we use the Tycho V-band magnitude along with expected magnitude differences from Pecaut & Mamajek (2013) for a star with the given $T_{\text{eff}}$.

4.2.1. Orbital analysis of HIP 65A and HIP 65B using Gaia

Gaia DR2 measured precise positions and proper motions for HIP 65A and HIP 65B, so we derived orbital element constraints from these measurements using the Linear Orbits for the Impatient algorithm (LOFTI; Pearce et al., submitted to ApJ). LOFTI uses rejection sampling to determine orbital element posterior probability distributions for stellar binaries derived from Gaia DR2 positions and proper motions. We ran LOFTI on the relative Gaia measurements for HIP 65B relative to HIP 65A until the rejection sampling algorithm had accepted 50,000 orbits, comprising our posterior orbit sample.

The Gaia measurements for the pair are not precise enough to constrain the orbital elements to a high degree. Additionally, HIP 65B has a slightly elevated Renormalised Unit Weight Error (RUWE) of 1.28, whereas RUWE $< 1.2$ indicates a well-behaved Gaia astrometric solution (Lindgren 2018), so the assumption of a pair of single stars on a Keplerian orbit may not be appropriate. Nevertheless, our results provide some meaningful limits on the orbital architecture of the system, as presented in Table 4. We find inclinations $109.2^\circ < i < 161.9^\circ$ comprise the majority of the posterior, making edge-on inclination consistent with HIP65Ab highly unlikely. Low eccentricity ($e < 0.5$) and periastron $> 75$ AU orbits are preferred.

5. Phase curve analysis for HIP 65Ab

A TESS phase folded light curve of HIP 65Ab is shown in Fig. 5 with the eclipses removed. The data are phase-folded with the orbital period and averaged into 100 bins that are $\sim 14$ minutes long, each with the contributions of about 350 individual flux measurements. For the individual flux measurements, we measure an rms scatter in the data points of $\sim 980$ ppm, and thus the statistical uncertainty in each bin of the light curve is approximately 53 ppm. A casual inspection shows that the light curve exhibits a characteristic orbital phase curve.

We fit sines and cosines of $\omega t$ and $2\omega t$ to the out-of-transit light curve, where $\omega$ is the angular frequency of the orbit, to represent various physical effects (see e.g. van Kerkwijk et al. 2010; Carter et al. 2011; Shporer 2017; Niraula et al. 2018; Shporer et al. 2019). We limited ourselves to just these four terms given the limited statistics in our folded out-of-eclipse light curve. The red curve in Fig. 5 is the $\cos \omega t$ term representing the illumination effect of the host star on the planet; the purple curve is the

Table 3. Stellar Properties for HIP 65B, companion to HIP 65A.

| Property          | HIP 65B | Source          |
|-------------------|---------|-----------------|
| 2MASS ID          | None, blended w. HIP 65A | 2MASS          |
| Gaia ID DR2       | 4923860051276722480 | Gaia           |
| TIC ID            | 616112169 | TESS           |
| Astrometric Properties                      |
| R.A.              | 00:00:44.28 | TESS           |
| Dec.              | -54:49:47.94 | TESS           |
| $\mu_{\text{R.A.}}$ (mas yr$^{-1}$) | -207.466 $\pm$ 0.086 | Gaia          |
| $\mu_{\text{Dec.}}$ (mas yr$^{-1}$) | -72.266 $\pm$ 0.081 | Gaia          |
| Parallax (mas)    | 16.117 $\pm$ 0.059 | Gaia          |
| Distance (pc)     | 61.94 $\pm$ 0.23 | Gaia          |
| Photometric Properties                      |
| V (mag)           | 16.55 $\pm$ 0.07 | †              |
| G (mag)           | 15.3877 $\pm$ 0.0008 | Gaia          |
| T (mag)           | 14.30 $\pm$ 0.014 | TESS           |

Notes. † V-band magnitude from Knapp & Nanson (2018).

FEROS) for the systemic velocity and RV-jitter. For the transit light curves a set of two limb darkening coefficients for each photometric bands are fitted along with the base line flux and variance of the light curve. The TESS PDC-SAP and FFI data were modelled separately to account for different error-properties.

To avoid Lucy-Sweeney bias of the eccentricity measurement (Lucy & Sweeney 1971) we constrain the eccentricity to be zero. To test for possible non-circular orbits, we run a separate MCMC with no constraint on the eccentricity. The data for HIP 65Ab, TOI-157b and TOI-169b are all consistent with circular orbits. We adopt median values of the posterior distributions and 68% confidence intervals for the models with eccentricity fixed to zero as the final parameters presented in Table 5, while quoting the 2 $\sigma$ upper limit of the eccentricity.

4.1. Stellar rotation and activity for HIP 65A

The PDC-SAP light curve for HIP 65A showed significant stellar variability attributed to star spots coming in and out of view as the star rotates, see Fig. 2. Using a Lomb-Scargle periodogram we find a rotation period of $P_{\text{rot}} = 13.2^{+1.4}_{-1.2}$ days. We flatten the light curve by fitting third order polynomials to chunks of the light curve while masking the transits. This type of spline filtering acts as a simple low pass filter (see e.g. Armstrong et al. 2016). The expected impact of stellar activity for a K-star with $P_{\text{rot}} = 13.2$ days on the RVs is on the order of $\sim 10$ m s$^{-1}$ (Suárez Mascareño et al. 2017, 2015). This is comparable to the uncertainty on the FEROS RVs and much smaller than the uncertainties of the CORALIE data. We find no correlation between RV-residuals to the best-fit model and stellar activity indicators, such as bisector span, FWHM of the CCF, Hα-index. We do thus not perform any correction for stellar activity.

4.2. Stellar companion to HIP 65A

HIP 65A is part of a visual binary separated by 3.95" on the sky. The two stars are associated with similar proper motion and parallax (Gaia Collaboration et al. 2018), as illustrated in Fig. 3. We denoted them HIP 65A and HIP 65B. Their angular separation on sky corresponds to 245 AU. HIP 65B is a M-dwarf with $T_{\text{eff}} = 3713^{+964}_{-280}$ K according to Gaia DR2. The work by Anders...
Fig. 2. TESS 2-min cadence data for HIP 65A spanning Sectors 1 and 2. The stellar rotational period of \(13.2^{+1.9}_{-1.4}\) days clearly shows up in the PDC-SAP flux. The light curve was flattened while masking the transits before modelling the transits.

Table 4. Orbital Parameter Posterior Distributions for HIP 65A and HIP 65B from Gaia Astrometry

| Parameter          | Median  | Mode   | 68% Min CI | 95% Min CI |
|--------------------|---------|--------|------------|------------|
| \(\log(a)\) (AU)  | 2.43    | 2.42   | (2.19, 2.51)| (2.18, 2.82)|
| \(e\)             | 0.31    | 0.08   | (0.0, 0.49) | (0, 0.67)  |
| \(i\) (°)         | 126.4   | 125.0  | (113.6, 136.5) | (109.2, 161.9) |
| \(\omega\) (°)    | 178.4   | 316.2  | (119.0, 341.8) | (17.9, 360.0) |
| \(\Omega\) (°)    | 104.4   | 90.0   | (78.6, 135.1) | (29.6, 178.4) |
| \(T_0\) (yr)      | 806.6   | 1319.6 | (-383.7, 1564.9) | (-7192.1, 2013.9) |
| \(\log[a(1-e)]\)  | 2.30    | 2.42   | (1.89, 2.49) | (1.73, 2.71) |

Notes. (a) Orbital parameters: semi-major axis (a), eccentricity (e), inclination (i), argument of periastron (\(\omega\)), longitude of nodes (\(\Omega\)), epoch of periastron passage (\(T_0\)), and periastron distance \([a(1-e)]\). (b) Posterior distributions are not Gaussian, so we report the 68% and 95% minimum credible intervals. (c) Inclination is defined relative to the plane of the sky, \(i = 90^\circ\) is edge-on. (d) In the absence of radial velocity information, there is a degeneracy between \(\omega\) and \(\Omega\), so we limit \(\Omega\) to be on the interval \([0, 180]\). If in the future radial velocity is obtained and \(\Omega > 180^\circ\), 180° should be added to both \(\Omega\) and \(\omega\).

Fig. 3. Multi-colour Digitized Sky Survey image of HIP 65A (centre cross-hair) and the nearby companion HIP 65B separated by 3.95” towards north. Their common proper motions are indicated as pink arrows. Blue squares are Gaia DR2 sources in the field, with Gaia magnitudes and parallaxes denoted.

Fig. 4. Selection of 100 orbits from the posterior sample of the fit of HIP65B relative to HIP65A using Gaia positions and proper motions. Inclination consistent with HIP65Ab is absent from our posteriors, and low eccentricities are preferred.

cos 2\(\omega\)t term to approximate the bulk of the ellipsoidal variations (‘ELVs’); and the orange curve is the sin \(\omega\)t term for the Doppler boosting effect (Loeb & Gaudi 2003; van Kerkwijk et al. 2010). The three terms were detected at the 12, 7, and 3.4 \(\sigma\) confidence levels, respectively, and there was no statistically significant amplitude for a sin 2\(\omega\)t term, where no physical effect is expected.

We next utilised the amplitudes of the ELV and Doppler boosting terms to make an independent determination of the planetary mass. Following the expressions and references in Shporer et al. (2019) we adopted a Doppler boosting coefficient in front of the \(K_{RV}/c\sin i\) term of \(4.2^{+1.5}_{-1.2}\) and an ELV coefficient...
Ment, in principle, determines the planetary mass. We therefore
\( q = \frac{R_p}{a} \) term of 1.25 ± 0.25, where \( K_{\text{RV}} \) is
the orbital radial velocity semi-amplitude of the host star, \( q \)
the planet to host star mass ratio, and \( a \) is the orbital radius
of the planet. Since we know the mass of the host star and the orbital
inclination to \( \sim 1^\circ \), either the Doppler boosting or ELV measure-
ment, in principle, determines the planetary mass. We therefore
carried out a Monte Carlo evaluation of the overall uncertainty
in the planet mass using both measurements (Joss & Rappaport
1984). From this analysis we find \( M_p = 3.4 \pm 0.6 \, M_J \), which is
in agreement with RV-derived mass of 3.213 ± 0.078 \( M_J \).

Finally, in regard to the out-of-transit light curve of HIP 65Ab, we explored what we can learn from the illumination
term which has an amplitude of 57 ppm. Because the estimated
equilibrium temperature of the planet at the sub-stellar point is
likely \( \lesssim 1400 \) K, we neglect any contribution from the thermal
emission of absorbed and reprocessed radiation from the host
star. We find that if the Bond albedo of the facing hemisphere
of the planet is allowed to be in the range of \( 0 - 0.5 \), then
the resultant likelihood distribution of planet radii, as inferred from
the illumination term, is close to 1 \( R_J \). On the other hand, if the
geometric albedo is constrained to be \( \lesssim 0.1 \), then the peak of
the radius distribution is close to our transit-based estimate of
2 \( R_J \). This low albedo is quite consistent with the results found
recently for WASP-18b (Shporer et al. 2019).

6. Results and discussion

For each system we list the final stellar and planetary parameters
in Table 5 with 1 \( \sigma \) errors. Figures 6 through 12 show the final
joint model fitted to the discovery and follow-up data.

6.1. HIP 65Ab

HIP 65Ab is an ultra short period (\( P = 0.98 \) days) Jupiter with
mass 3.213 ± 0.078 \( M_J \). Its radius, \( R = 2.03^{+0.61}_{-0.49} \, R_J \), is poorly
constrained as the transit is extremely grazing with impact para-
meter \( b = 1.169^{+0.097}_{-0.072} \). The planet is thus barely transiting with
less than half its disk covering the host star during transit. The
V-shaped, relatively shallow, transit model can be seen in Figs.
6 and 7 plotted along with the follow-up light curves and TESS

![Fig. 5. Out-of-transit folded and binned light curve for HIP 65Ab. The red,
purple, and orange curves are sinusoids meant to represent the il-
mulation, ellipsoidal light variations, and Doppler boosting effects,
respectively (see text for details). The blue curve is the sum of these
effects, and represents the best fit of this model to the out-of-transit light curve.
](image)

data. Figure 12 shows the phase folded RVs showing the large
semi-amplitude of 754 ± 5 m s\(^{-1}\).

HIP 65A is found to be a bright (\( V = 11.1 \)) main sequence
K-star with \( T_{\text{eff}} = 4590 \pm 49 \) K, \( R_* = 0.724 \pm 0.009 \, R_\odot \) and
\( M_* = 0.781 \pm 0.027 \, M_\odot \). We find clear signs of stellar ro-
rotation in the TESS light curve corresponding to a rotation pe-
riod of \( P_{\text{rot}} = 13.2^{+1.9}_{-1.5} \) days. HIP 65A has an associated stellar
companion, HIP 65B, separated by 3.95° with similar distance
and proper motion. Based on Gaia DR2 data we conclude that
HIP 65B is an M-dwarf separated by 269 AU. With such a separa-
tion and high mass ratio \( q = 0.38 \) the protoplanetary disk is not
expected to be affected by the presence of the stellar companion
(Artymowicz & Lubow 1994; Patience et al. 2008).

The orbital analysis of HIP 65A+B using Gaia measure-
ments indicates that the mutual inclination is less than 0.5. This
still includes orbital solutions where the the Lidov-Kozai mecha-
nism is invoked, which could be used to explain the architecture
of the system (Lidov 1962; Kozai 1962). A requirement for such
a process to occur is that the mutual inclination between the two
orbits at high period ratio is large enough. From then, the an-
gular momentum exchange between the two orbits will induce
phase-opposed oscillations of the eccentricity and inclination of
the inner orbit. At high eccentricity phases, tidal dissipation will
take place during the periastron passages, leading the orbit of
the planet to shrink. This mechanism was already successfully
introduced to explain the observations of planets in binary sys-
tems (e.g. Wu & Murray 2003; Fabrycky & Tremaine 2007).

Measuring the spin-orbit misalignment between the central
star and the inner planet could help at selecting the mechanism
responsible for the current architecture of the system. If a signifi-
cant misalignment is found, the Lidov-Kozai mechanism will be
favoured. If, on the other hand, the spin axis of the star is aligned
with the normal to the inner orbit, then the Lidov-Kozai mech-
anism will be excluded because the planet would not have been
misaligned from its original orbit.

Figure 13 shows mass and radius for known exoplanets
with HIP 65Ab, TOI-157b and TOI-169b over-plotted in blue.
HIP 65Ab does appear to have an unusually large radius but this
measurement might be overestimated due to the grazing nature
of the transit. Close in gas planets are found to be inflated, as the
proximity to the host star can inhibit thermal contraction (Baraffe
et al. 2010; Batygin & Stevenson 2010). As seen in Fig. 14
HIP 65Ab receives 642 times more insolation flux than that of
the Earth. Given the mass and insolation flux it is unlikely that
HIP 65Ab is larger than 1.5 \( R_J \).

The effects of the large planetary mass and radius, relative
to the host star, are evident in the TESS light curve. Our anal-
ysis of the phase curve yields an illumination effect amplitude
of 57.5 ± 4.7 ppm, ELV amplitude 30.0 ± 4.7 ppm, as well as
Doppler boosting effect 15.4 ± 4.5 ppm. The mass derived on
the basis of the two latter terms is 3.4 ± 0.6 \( M_J \), in agreement
with the independently derived RV-mass. We estimate the geo-
metric Bond albedo to be \( \lesssim 0.1 \), but cannot constrain it further
due to large uncertainties on the radius. A study by Wong et al.
(in prep.) presents a systematic phase curve analysis of TOIs for
the first year of TESS operation, which are in agreement with our
results.

6.2. TOI-157b

TOI-157b is an inflated hot Jupiter with orbital period \( P =
2.08 \) days, mass 1.18 ± 0.13 \( M_J \) and \( R = 1.29 \pm 0.02 \, R_J \). The
photometry from the ground-based follow-up and TESS is pre-
sented in Fig. 9. The RVs are shown in Fig. 10, including two
Table 5. Median values and 68% confidence intervals for HIP 65A, TOI-157 and TOI-169.

Stellar Parameters:

| Parameter          | TOI-157 | TOI-169 |
|--------------------|---------|---------|
| M_\star \ (M_\odot) | 0.781 ± 0.027 | 0.948 ± 0.023 |
| R_\star \ (R_\odot) | 0.7242 ± 0.0081 | 1.167 ± 0.017 |
| L_\star \ (L_\odot) | 0.2099 ± 0.0077 | 1.047 ± 0.055 |
| \rho_\star \ (g/cm^3) | 2.898 ± 0.085 | 0.842 ± 0.029 |
| log g_\star \ (cgs) | 4.611 ± 0.010 | 4.281 ± 0.011 |
| T_{eff} \ (K) | 4590 ± 90 | 5404 ± 70 |
| [Fe/H] \ (dex) | 0.18 ± 0.08 | 0.24 ± 0.09 |
| Age \ (Gyr) | 4.11 ± 0.3 | 12.82 ± 0.74 |
| A_V \ (mag) | 0.02 ± 0.01 | 0.12 ± 0.08 |
| d_\star \ (pc) | 61.89 ± 0.08 | 362.1 ± 28 |
| v sin i \ (km s^{-1}) | < 2.5 | < 2.5 |
| P_{rot} \ (days) | 13.21 ± 1.9 | 13.21 ± 1.9 |

Planetary Parameters:

| Parameter | TOI-65Ab | TOI-157b | TOI-169b |
|-----------|----------|----------|----------|
| R_P \ (R_\oplus) | 2.03 ± 0.61 | 2.186 ± 0.023 | 1.086 ± 0.081 |
| M_P \ (M_\oplus) | 3.21 ± 0.078 | 1.18 ± 0.11 | 0.791 ± 0.065 |
| P \ (days) | 0.989734 ± 0.000031 | 2.048543 ± 0.000023 | 2.255447 ± 0.000063 |
| T_C \ (BJD_{TDB}) | 58326.10418 ± 0.00011 | 58326.5471 ± 0.00021 | 58327.4417 ± 0.00065 |
| a \ (AU) | 0.01782 ± 0.000020 | 0.03138 ± 0.000025 | 0.03524 ± 0.000069 |
| i \ (Degrees) | 77.18 ± 0.39 | 82.01 ± 0.13 | 80.99 ± 0.38 |
| b \ (Transit Impact parameter) | 1.169 ± 0.077 | 0.8045 ± 0.068 | 0.9221 ± 0.098 |
| e \ (Orbital eccentricity) | 0 (adopted, 2\sigma < 0.02) | 0 (adopted, 2\sigma < 0.21) | 0 (adopted, 2\sigma < 0.12) |
| K \ (RV semi-amplitude (m/s)) | 753.3 ± 5.0 | 192 ± 20 | 110 ± 16 |
| T_{eq} \ (Equilibrium temperature (K)) | 1411 ± 15 | 1588 ± 21 | 1751 ± 59 |
| R_P/R_\star | 0.287 ± 0.068 | 0.1129 ± 0.0054 | 0.0866 ± 0.0031 |
| a/R_\star | 5.289 ± 0.045 | 5.785 ± 0.069 | 5.88 ± 0.16 |
| δ \ (Transit depth (fraction)) | 0.082 ± 0.034 | 0.01283 ± 0.00011 | 0.00756 ± 0.00036 |
| Depth | 0.01094 ± 0.00033 | 0.01283 ± 0.00011 | 0.00756 ± 0.00036 |
| τ | 0.01637 ± 0.00013 | 0.02309 ± 0.00076 | 0.0351 ± 0.0050 |
| T_{14} | 0.03274 ± 0.00025 | 0.08941 ± 0.00052 | 0.0711 ± 0.0012 |
| T_{FWHM} | 0.01637 ± 0.00013 | 0.06631 ± 0.00067 | 0.03587 ± 0.00076 |
| ρ_P \ (Density (g/cm^3)) | 0.48 ± 0.38 | 0.686 ± 0.081 | 0.76 ± 0.14 |
| log g_P \ (cgs) | 3.29 ± 0.24 | 3.247 ± 0.046 | 3.219 ± 0.099 |
| Θ | 0.072 ± 0.031 | 0.0606 ± 0.0064 | 0.0445 ± 0.0029 |
| ⟨F⟩ | 0.899 ± 0.639 | 1.446 ± 0.070 | 1.964 ± 0.009 |

FEROS RVs which were not used in the analysis in the end, as they do not help constrain the amplitude of the RV curve when fitting an offset between CORALIE and FEROS.

6.3. TOI-169b

TOI-169b has the longest period of the three planets presented in this study with P = 2.26 days. It is a low-mass hot Jupiter with mass 0.79 ± 0.06 M_\oplus and radius R = 1.086^{+0.041}_{-0.042} R_\oplus. TOI-169b is found to be a main sequence G1-star with T_{eff} = 5880 ± 50 K, R_\star = 1.288 ± 0.020 R_\odot and M_\star = 1.1477^{+0.0009}_{-0.0013} M_\odot.

Despite having the longest orbital period of the three planets presented in this study, TOI-169b receives the highest insolation flux: 1403 times that of Earth, corresponding to an equilibrium temperature of 1715 ± 21 K. Figure 14 shows the known population of exoplanets plotted in insolation-radius space. TOI-169b is located right at the edge of the Neptune desert. Given its irradiation, TOI-169 is unusually dense, which could support a scenario of the atmospheric volatile layer being stripped away by photo-evaporation, to a point where the self-gravity of the planet is strong enough to withstand the atmospheric escape (Lopez & Fortney 2014; Mordasini et al. 2015). During this process, less massive planets could completely lose their outer layer and end up as a naked core at the bottom of the desert (Owen & Lai...
2018), thus joining the large population of mainly Kepler planets seen in Fig. 14.

7. Conclusions

We have presented the discovery and mass determination of three new Jovian planets HIP 65Ab, TOI-157b and TOI-169b from the TESS mission. We based our analysis on both 2-min cadence and FFI data from TESS spanning multiple Sectors in the first year of operations as well as numerous ground-based photometric observations. Light curves were modelled jointly with RVs from the CORALIE and FEROS spectrographs. Using SOAR speckle imaging we rule out close stellar companions for all three host stars.

HIP 65Ab is an ultra short period massive hot Jupiter with a period of 0.98 days, orbiting one component of a stellar binary. Despite the proximity to its host star, HIP 65Ab receives the least amount of radiation out of the three planets presented in this study. TOI-157b and TOI-169b both receive more than 1000 times the Earth’s insolation flux. TOI-157b orbits a giant star with a 0.03 AU separation. TOI-169b is bordering the Neptune desert and can thus help solve the conundrum of which mechanisms are responsible for the shortage of close-in giant planets.

Acknowledgements. We thank the Swiss National Science Foundation (SNSF) and the Geneva University for their continuous support to our planet search programs. This work has been in particular carried out in the framework of the National Centre for Competence in Research ‘PlanetS’ supported by the Swiss National Science Foundation (SNSF). This publication makes use of The Data & Analy- 

sis Center for Exoplanets (DACE), which is a facility based at the University of Geneva (CH) dedicated to extrasolar planets data visualisation, exchange and analysis. DACE is a platform of the Swiss National Centre of Competence in Research (NCCR) PlanetS, federating the Swiss expertise in Exoplanet research. The DACE platform is available at https://dace.unige.ch. This paper in- cludes data collected by the TESS mission. Funding for the TESS mission is provided by the NASA Explorer Program. Resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center for the production of the SPOC data products. This work has made use of data from the European Space Agency (ESA) mission Gaia (https://www.cosmos.esa.int/gaia), processed by the Gaia Data Processing and Analysis Consortium (DPAC, https://www.cosmos. esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been pro- vided by national institutions, in particular the institutions participating in the Gaia Multilateral Agreement. This research has made use of Aladin sky atlas de- veloped at CDS, Strasbourg Observatory, France. This work makes use of observa- 
tions from the LCOGT network. This work is partly supported by ISPS KAK- 
ENHI Grant Numbers JP15H02063, JP18H01265, JP18H05439, JP18H05442, and JST PRESTO Grant Number JPMJPR1775. The IRSF project is a collabo- 

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A&A proofs: manuscript no. Three_HJs_from_TESS

Four ACES; grant agreement No 724427. L.A.P. is supported by the National Science Foundation Graduate Research Fellowship program under Grant No. DGE-1746600. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation. Includes data collected under the NGTS project at the ESO La Silla Paranal Observatory. The NGTS facility is funded by the University of Warwick, the University of Leicester, Queen’s University Belfast, the University of Geneva, the Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR, under the ‘Großinvestition GI-NGTs’), the University of Cambridge and the UK Science and Technology Facilities Council (STFC; project references ST/M001962/1 and ST/S002642/1). Staff from the University of Warwick acknowledge support from STFC consolidated grant ST/P000495/1.
Table A.1. Radial velocity measurements from CORALIE and FEROS for HIP 65A.

| BJD    | RV  | \(\sigma_{RV}\) | BIS  | Instrument |
|--------|-----|-----------------|------|------------|
| (- 2,400,000) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) |            |
| 58382.793749 | 22105.0 | 25.5 | -40.7 | CORALIE |
| 58406.764434 | 20526.8 | 66.6 | -118.2 | CORALIE |
| 58408.788981 | 20652.1 | 28.6 | -134.2 | CORALIE |
| 58410.498946 | 21177.3 | 31.6 | -64.6 | CORALIE |
| 58410.586650 | 20825.2 | 31.5 | -49.1 | CORALIE |
| 58410.732244 | 20533.6 | 31.2 | 21.7 | CORALIE |
| 58411.498626 | 21082.4 | 41.5 | -51.7 | CORALIE |
| 58411.591838 | 20749.7 | 32.7 | -169.6 | CORALIE |
| 58411.648374 | 20664.0 | 28.6 | -73.4 | CORALIE |
| 58412.594656 | 20602.4 | 43.3 | -274.9 | CORALIE |
| 58419.531857 | 20635.3 | 31.1 | -71.7 | CORALIE |
| 58426.579955 | 20998.7 | 34.5 | -88.5 | CORALIE |
| 58465.662441 | 20607.2 | 20.7 | -63.9 | CORALIE |
| 58478.592577 | 21109.9 | 14.5 | -42.7 | CORALIE |
| 58479.593054 | 21206.5 | 15.5 | -47.2 | CORALIE |
| 58487.570334 | 21766.1 | 18.0 | -71.7 | CORALIE |
| 58500.538320 | 22047.5 | 28.3 | -32.1 | CORALIE |
| 58408.66413 | 20733.1 | 10.8 | -35 | FEROS |
| 58411.74045 | 20675.5 | 9.3 | -29 | FEROS |
| 58412.64109 | 20671.7 | 8.3 | -52 | FEROS |
| 58413.54882 | 20791.6 | 7.8 | -29 | FEROS |
| 58414.63269 | 20630.9 | 8.3 | -35 | FEROS |
| 58415.63086 | 20635.0 | 9.7 | -4 | FEROS |
| 58416.59652 | 20608.9 | 8.3 | 15 | FEROS |
| 58418.59589 | 20662.7 | 8.3 | -40 | FEROS |
| 58419.56945 | 20659.0 | 8.6 | -14 | FEROS |
| 58423.65772 | 21140.9 | 8.7 | -57 | FEROS |
| 58424.57114 | 20896.8 | 8.4 | -26 | FEROS |
| 58428.72879 | 21898.1 | 9.5 | -15 | FEROS |
| 58430.68560 | 21856.6 | 8.8 | 15 | FEROS |
| 58450.63188 | 21655.5 | 8.6 | -17 | FEROS |
| 58451.56707 | 21856.7 | 9.3 | 55 | FEROS |
| 58451.58556 | 21762.3 | 8.1 | -35 | FEROS |
| 58452.57292 | 21747.4 | 8.8 | -9 | FEROS |

Appendix A: RV data
Fig. 6. Ground based photometric follow-up data for HIP 65Ab from LCO-SSO, MKO, PEST and NGTS. The open circles are data binned to 5 min.

Fig. 7. Phase folded transit light curve for HIP 65Ab including two Sectors data and follow-up photometry from Figs. 2 and 6 in grey. The blue circles are data binned to 5 min. The points with large scatter come from the NGTS 10 sec cadence observations.

Fig. 8. RVs from CORALIE and FEROS for HIP 65A, phase folded on the ephemeris of the planet. Error bars are included, but too small to show.
Fig. 9. Top: Ground based photometric follow-up data for TOI-157b. The open circles are data binned to 10 min. Bottom: Phase folded transit light curve for TOI-157b including TESS data and follow-up photometry in grey. The blue circles are the same data binned to 10 min.

Fig. 10. CORALIE and FEROS RVs for TOI-157, phase folded on the ephemeris for TOI-157b.

Table A.2. Radial velocity measurements from CORALIE and FEROS for TOI-157. The two FEROS RVs were not included in the global modelling of the system.

| BJD     | RV     | σ_{RV} | BIS | Instrument |
|---------|--------|--------|-----|------------|
| (- 2,400,000) | (m s\(^{-1}\)) | (m s\(^{-1}\)) | (m s\(^{-1}\)) |            |
| 58394.715066 | -8782.2 | 118.7 | -130.7 | CORALIE |
| 58397.866965 | -8941.8 | 72.6 | -59.6 | CORALIE |
| 58414.670583 | -8686.6 | 52.6 | 15.3 | CORALIE |
| 58417.691914 | -8498.7 | 62.6 | -35.8 | CORALIE |
| 58418.770424 | -8555.5 | 55.2 | -14.9 | CORALIE |
| 58419.814201 | -8543.7 | 53.7 | -36.5 | CORALIE |
| 58427.857757 | -8658.9 | 53.5 | -7.8 | CORALIE |
| 58433.659427 | -8876.8 | 75.0 | -105.2 | CORALIE |
| 58455.780420 | -8742.2 | 44.4 | -120.3 | CORALIE |
| 58456.769193 | -8609.9 | 90.3 | -117.4 | CORALIE |
| 58457.708950 | -6811.1 | 73.9 | 38.3 | CORALIE |
| 58458.705351 | -8951.0 | 79.1 | -124.8 | CORALIE |
| 58460.665537 | -9183.8 | 211.2 | 414.9 | CORALIE |
| 58461.712853 | -8534.8 | 57.9 | -40.7 | CORALIE |
| 58462.651604 | -8907.4 | 58.5 | -3.4 | CORALIE |
| 58463.574905 | -8503.6 | 59.6 | -12.2 | CORALIE |
| 58463.809868 | -8526.8 | 50.3 | -130.3 | CORALIE |
| 58464.562176 | -8926.0 | 51.5 | 106.0 | CORALIE |
| 58464.749963 | -8958.1 | 65.2 | 64.1 | CORALIE |
| 58467.599544 | -8571.1 | 61.5 | -15.2 | CORALIE |
| 58471.590055 | -8625.6 | 57.7 | -90.1 | CORALIE |
| 58474.675323 | -8691.5 | 50.8 | 44.9 | CORALIE |
| 58475.657076 | -8538.2 | 43.6 | 139.4 | CORALIE |
| 58486.705154 | -8543.7 | 54.0 | -47.5 | CORALIE |
| 58381.883623 | -8663.9 | 16.3 | 25 | FEROS |
| 58383.881139 | -8672.1 | 14.9 | 61 | FEROS |
Fig. 11. Top: Ground based photometric follow-up data for TOI-169. The open circles are data binned to 10 min. Bottom: Phase folded transit light curve for TOI-169 including TESS data and follow-up photometry, also with 10 min bins over-plotted as blue circles.

Fig. 12. CORALIE and FEROS RVs for TOI-169, phase folded on the ephemeris for TOI-169b.

Fig. 13. Mass and radius for known exoplanets extracted from NASA Exoplanet Archive. Only planets with 20% precision on their mass are included. HIP 65Ab, TOI-157b and TOI-169b are plotted in blue.

Fig. 14. Insolation flux relative to Earth plotted against radii for known exoplanets extracted from NASA Exoplanet Archive. The orange contours indicate point density (not occurrence) HIP 65Ab, TOI-157b and TOI-169b are plotted in blue.
Table A.3. Radial velocity measurements from CORALIE and FEROS for TOI-169.

| BJD (- 2,400,000) | RV (m s\(^{-1}\)) | \(\sigma_{RV}\) (m s\(^{-1}\)) | BIS (m s\(^{-1}\)) | Instrument |
|-------------------|---------------------|-------------------------------|-------------------|------------|
| 58411.74975       | 43526.9             | 14.0                          | 68                | FEROS      |
| 58414.79857       | 43754.4             | 16.3                          | -66               | FEROS      |
| 58418.63748       | 43562.4             | 12.1                          | 17                | FEROS      |
| 58419.65549       | 43671.5             | 10.6                          | -28               | FEROS      |
| 58423.68635       | 43716.1             | 11.5                          | 23                | FEROS      |
| 58428.71918       | 43688.5             | 12.7                          | 15                | FEROS      |
| 58429.67408       | 43529.5             | 11.2                          | 5                 | FEROS      |
| 58430.75367       | 43716.2             | 11.5                          | -7                | FEROS      |
| 58450.72036       | 43696.4             | 10.4                          | 56                | FEROS      |
| 58451.57625       | 43586.1             | 9.8                           | 29                | FEROS      |
| 58648.913708      | 43623.24            | 63.7                          | 119.9             | CORALIE    |
| 58657.885639      | 43570.95            | 38.2                          | -27.9             | CORALIE    |
| 58666.832642      | 43601.87            | 55.4                          | -66.4             | CORALIE    |
| 58669.821282      | 43720.12            | 41.9                          | 97.4              | CORALIE    |
| 58677.860677      | 43523.81            | 53.0                          | -17.5             | CORALIE    |
| 58679.934507      | 43490.82            | 42.3                          | 18.9              | CORALIE    |