The mass–radius relationship for very low mass stars: four new discoveries from the HATSouth Survey

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ABSTRACT
We report the discovery of four transiting F-M binary systems with companions between 0.1 and 0.2 M⊙ in mass by the HATSouth survey. These systems have been characterized via a global analysis of the HATSouth discovery data, combined with high-resolution radial velocities and accurate transit photometry observations. We determined the masses and radii of the component stars using a combination of two methods: isochrone fitting of spectroscopic primary star parameters and equating spectroscopic primary star rotation velocity with spin–orbit synchronization. These new very low mass companions are HATS550-016B (0.110±0.005 M⊙, 0.147±0.006 R⊙), HATS551-019B (0.173±0.010 M⊙, 0.183±0.006 R⊙), HATS552-021B (0.132±0.014 M⊙, 0.154±0.006 R⊙) and HATS553-001B (0.203±0.002 M⊙, 0.222±0.001 R⊙). We examine our sample in the context of the radius anomaly for fully convective low-mass stars. Combining our sample with the 13 other well-studied very low mass stars, we find a tentative 5 per cent systematic deviation between the measured radii and theoretical isochrone models.

Key words: binaries: eclipsing -- stars: low-mass.

1 INTRODUCTION
‘Very low mass stars’ (VLMSs), with masses between 0.08 and 0.3 M⊙, are the most dominant subset of the stellar population (e.g. Kroupa 2001). These stars are thought to have fully convective interiors and hydrogen fusion in their cores, distinguishing them from higher mass stars and brown dwarfs, respectively (see review by Chabrier & Baraffe 2000). Mass and radius are two of the most fundamental measurements for stars. Previous studies have shown that the radii of subsolar mass stars are underpredicted by theoretical interior models at the 5–10 per cent level (e.g. Torres & Ribas 2002; Ribas 2006; Torres, Andersen & Giménez 2010; Feiden & Chaboyer 2012; Spada et al. 2013). The interior structure of the fully convective VLMSs is different from that of higher mass, partially radiative stars, and therefore, warrants a more thorough, independent examination.

The vast majority of masses and radii come from dynamical measurements of binary systems. One explanation for the radius anomaly is that when these M-dwarf binaries are spun-up by tidal interactions, the speed-up of the internal dynamo then leads to increased magnetic activities, suppressing convection and increasing star-spot activity (e.g. López-Morales & Ribas 2005; Ribas...
It remains difficult to test stellar models for the VLMS population, given that metallicities and precision (better than 10 per cent) mass radius measurements are available for only 13 previous objects (see Section 4.5). In contrast, we know the masses and radii of ~40 exoplanets to better than 5 per cent precision, which has led to more thorough examinations of planet interior models (e.g. Laughlin, Crismani & Adams 2011; Swift et al. 2012). The radii of standalone, close-by M-dwarfs can be measured via interferometry (e.g. Ségransan et al. 2003), but the masses must be inferred from empirical mass–luminosity relationships. Dynamical masses of binaries can be obtained via astrometric orbit measurements (e.g. Simon et al. 2013). Double-lined M-M eclipsing binary systems provide accurate, model-independent mass and radius measurements (Metcalfe et al. 1996; Carter et al. 2011; Doyle et al. 2011; Irwin et al. 2011; Nefs et al. 2013), but these systems are relatively rare. In addition, the accuracy of M-M binary-derived system parameters may suffer from M-dwarf activity and unaccounted spot variability, and may not be as reliable as previously thought (Feiden & Chaboyer 2012).

Photometric transit surveys have led to a rapid expansion in the population of transiting exoplanets. VLMSs have radii comparable to that of gas-giant planets and are often found as companions in binary systems to solar-type stars. These F-M binaries exhibit similar transit signals as hot-Jupiter systems and can be easily identified by transiting planet surveys. The population of well-characterized VLMSs can be greatly extended by including single-lined F-M binaries (e.g. Pont et al. 2005, 2006; Beatty et al. 2007; Fernandez et al. 2009; Triaud et al. 2013).

There are a number of approaches towards measuring the mass and radius of M-dwarf companions in single-lined F-M binary systems. The primary star properties can be obtained by combining spectroscopic analysis with stellar evolution models. The precision of the measured companion mass and radius is limited by the uncertainty in the primary star properties. For orbital companions of substantial mass, the rotation of the primary star is quickly synchronized with the companion orbital period. Fundamental system parameters derived from transit light curves, combined with rotational velocities measured from spectra, can yield relatively model-independent masses and radii for both components of a binary system (e.g. Beatty et al. 2007; Fernandez et al. 2009).

In this study, we present the discovery of four single-lined stellar systems with 0.1–0.2 M☉ VLMS companions. These low-mass eclipsing binaries were identified by the HATSouth survey (Bakos et al. 2013). The discovery and follow-up observations are detailed in Section 2. Analysis of the individual systems, including spectral classifications of the primary star, global modelling of the light curves and radial velocity data and descriptions of the methods used to derive the mass and radius of the companions, can be found in Section 3. Section 4 discusses these new discoveries in the context of existing VLMS systems and examines the mass–radius anomaly in the VLMS regime.

2 OBSERVATIONS

2.1 HATSouth photometric detection

The transiting VLMS systems were identified from photometric observations by the HATSouth global network. HATSouth consists of six telescope units spread over three sites, SSO in Australia, LCO in Chile and the HESS site in Namibia, providing continuous monitoring of 128 deg² fields in the southern sky (Bakos et al. 2013). Each unit consists of four 0.18 m /2.8 Takahasi astrographs and Apogee Alta-U16M D9 4 K × 4 K front illuminated CCD cameras, with 9 μm pixels, and a plate scale of 3.7 arcsec pixel⁻¹. The four telescopes are offset by 4°, allowing four adjacent 4° × 4° fields to be simultaneously monitored. The observations are made at 4 min cadence in the r-band. Each field is monitored for ~2 months by a unit at each HATSouth station. Aperture photometry is performed on the reduced frames and detrended using external parameter decorrelation (Bakos et al. 2007) and the trend filtering algorithm (TFA; Kovács, Bakos & Noyes 2005). Objects exhibiting periodic transit signals are identified using the Box-fitting Least-Squares technique (Kovács, Zucker & Mazeh 2002).

The HATSouth discovery light curves for the systems presented in this study are shown in Fig. 1 and are summarized in Table 1. Details of our planetary candidate selection, vetting and confirmation process can be found in the recent HATSouth publications (Bayliss et al. 2013; Mohler-Fischer et al. 2013; Penev et al. 2013).

2.2 Identification of stellar mass binaries by ANU 2.3 m/WiFeS

Spectroscopic follow-up of HATSouth candidates starts with reconnaissance spectroscopic observations, at high signal-to-noise (S/N) and low–medium resolution, to determine preliminary primary star properties and to search for high-amplitude radial velocity variations (>2 km s⁻¹). These observations allow efficient identification of non-planetary systems, such as F-M binaries, by providing an initial mass estimate for the primary star and any secondary companion found. The reconnaissance observations are summarized in Table 2.

Initial spectroscopic observations of the targets were obtained using the Wide Field Spectrograph (WiFeS) on the ANU 2.3 m telescope (Dopita et al. 2007), located at SSO, Australia.

First, a low-resolution (R = λ/Δλ = 3000) spectrum covering the wavelength region 3500–6000 Å was used to obtain an initial stellar classification of the target star. The flux calibrated spectrum was fitted to a grid of synthetic spectra from Gustafsson et al. (2008). The details of the low-resolution spectral reduction and analysis, including fitting of the stellar properties, are given in Bayliss et al. (2013). These stellar parameters are later refined using high-resolution spectra (see Section 3.1).

Subsequent medium resolution, multi-epoch radial velocity observations were performed with WiFeS at R = 7000, observed at phase quadratures of the photometric ephemeris, where the potential velocity variation is greatest. In the case of stellar binaries, the radial velocity variations are often apparent with two well-time exposures. Combined with the WiFeS stellar parameters, the WiFeS radial velocity orbit provides an initial mass estimate of the companions and affects their prioritization for further follow-up studies. The WiFeS velocities were not included in the final system
Figure 1. HATSouth discovery light curves of the four VLMS systems, including close-ups of the transit event. The best-fitting models from Section 3.2 are plotted in red.

analysis, since fewer lower resolution observations do not contribute greatly to improving the precision of the measured radial velocity orbit.

2.3 High-resolution spectroscopic follow-up

Radial velocity measurements derived from high-resolution spectroscopic observations were obtained for the VLMS systems using the Echelle spectrograph on the ANU 2.3 m telescope at SSO, the fibre-fed echelle spectrograph CORALIE on the Swiss Leonard Euler 1.2 m telescope (Queloz et al. 2000) at La Silla Observatory (LSO), Chile, and the fibre-fed echelle spectrograph FEROS on the MPG/ESO 2.2 m telescope (Kaufer & Pasquini 1998) at LSO. The observations are summarized in Table 2. Descriptions of the data reduction and analysis for CORALIE and FEROS can be found in Penev et al. (2013, also see Jordán et al. in preparation). This is the first time we have used the ANU 2.3 m Echelle to monitor HATSouth targets; a description of these observations is presented below. The observations are listed in Table 1, with the radial velocities plotted in Figs 1–4.

2.3.1 ANU 2.3 m/Echelle

High-resolution spectra of the systems were obtained using the Echelle spectrograph on the ANU 2.3 m telescope. The Echelle was configured to a 1.8 arcsec wide slit, delivering a resolution of $R = 24000$ and velocity dispersion of 4.0 km s$^{-1}$ pixel$^{-1}$, in the
Table 1. Summary of photometric observations.

| Facility      | Date(s)                  | Filter | Number of images | Cadence (s) |
|---------------|--------------------------|--------|------------------|-------------|
| HATS550-016   | 2009/09/28–2010/12/20    | r′     | 8726             | 240         |
| FTS/Merope    | 2012/11/17               | i′     | 160              | 60          |
| MPG/ESO 2.2 m/GROND | 2012/12/08         | g′, r′, i′, z′ | 187           | 145         |
| MPG/ESO 2.2 m/GROND | 2012/12/08         | r′     | 185              | 145         |
| HATS551-019   | 2009/09/09–2010/04/29    | r′     | 5274             | 240         |
| PEST          | 2012/12/23               | Rc     | 168              | 120         |
| HATS551-021   | 2009/09/09–2010/04/29    | r′     | 5274             | 240         |
| HATS553-001   | 2009/09/17–2010/09/10    | r′     | 10703            | 240         |
| PEST          | 2012/12/22               | Rc     | 92               | 120         |

Table 2. Summary of spectroscopic observations.

| Facility      | Date range                  | Resolution | Wavelength coverage (Å) | Number of observations |
|---------------|-----------------------------|------------|-------------------------|-----------------------|
| HATS550-016   | 2012/05/11–2012/08/07       | 3000       | 3500–6000               | 2                     |
| ANU 2.3 m/WiFeS | 2012/08/04–2012/10/31     | 7000       | 5200–7000               | 16                    |
| Euler 1.2 m/CORALIE | 2012/08/25–2012/11/11   | 60 000     | 3850–6900               | 7                     |
| ANU 2.3 m/Echelle | 2012/12/04–2012/12/06     | 24 000     | 4200–6725               | 7                     |
| HATS551-019   | 2010/10/28–2011/02/18      | 60 000     | 3850–6900               | 3                     |
| Euler 1.2 m/CORALIE | 2010/11/26–2011/04/19   | 7000       | 5200–7000               | 4                     |
| ANU 2.3 m/Echelle | 2013/03/23–2013/04/01     | 24 000     | 4200–6725               | 7                     |
| HATS551-021   | 2010/10/28–2011/02/18      | 60 000     | 3850–6900               | 3                     |
| Euler 1.2 m/CORALIE | 2010/11/26–2011/09/17   | 7000       | 5200–7000               | 3                     |
| ANU 2.3 m/WiFeS | 2011/09/09–2011/09/10     | 48 000     | 3500–9200               | 2                     |
| MPG/ESO 2.2 m/FEROS | 2011/09/09–2011/09/17 | 3000       | 3500–6000               | 1                     |
| ANU 2.3 m/Echelle | 2013/03/23–2013/04/01     | 24 000     | 4200–6725               | 7                     |
| HATS553-001   | 2012/05/08                  | 3000       | 3500–6000               | 1                     |
| ANU 2.3 m/WiFeS | 2012/05/09–2012/05/09     | 7000       | 5200–7000               | 2                     |
| ANU 2.3 m/Echelle | 2013/03/23–2013/04/01     | 24 000     | 4200–6725               | 7                     |

spectral range 4200–6725 Å, over 20 echelle orders. The detector is a 2 K × 2 K CCD with a gain of 2 e− ADU⁻¹ and read noise of 2.3 ADU/pixel⁻¹, and binned two times in the spatial direction. A number of instrument limitations prevent us from achieving better than 500 ms⁻¹ velocity precision. For example, the instrument is mounted on the Nasmyth focus, not in a temperature stabilized environment; the low efficiency of the spectrograph limits the study to only bright stars (<13.5 V mag). The data were reduced with the IRAF¹ package CCDPROC and extracted using ECHELLE. A rapidly rotating B-star spectrum is divided through each observation to remove the blaze function. A low-order spline interpolation is then used to continuum normalize each spectrum. The wavelength solution was provided by ThAr arc lamp exposures that bracketed each science exposure.

¹ IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

Radial velocity measurements were obtained by cross-correlating the object spectra against a series of radial velocity standard star spectra taken on the same night. The radial velocities derived from selected echelle orders not severely contaminated by telluric absorption features were sigma clipped and weight averaged according to their respective cross correlation function (CCF) heights and S/Ns. Typically, 15 echelle orders were used in the cross-correlations. A velocity and the associated uncertainty were determined for each order, from which the weighted average and standard deviation were calculated and adopted as the measured velocity. For stable HAT-South candidates with V mag ≈ 13, the long-term root-mean-squared (rms) velocity scatter of the instrument is ∼1.0 km s⁻¹. Stellar parameters were also derived from the Echelle spectra; the process is described in detail in Section 3.1.

2.4 Photometric follow-up

Follow-up photometric confirmations for the transit events of HATS550-016B, HATS551-019B, and HATS553-001B were made...
Transiting very low mass stars from HATSouth

Figure 2. Top: HATS550-016 radial velocities and the Keplerian orbit fit. ANU 2.3 m Echelle data are plotted as squares, and CORALIE data as triangles. Bottom: follow-up transit light curve and model fit.

using the Meropex camera on the 2 m Faulkes Telescope South (FTS) located at SSO, the Gamma-Ray Burst Optical/Near-Infrared Detector (GROND) on the MPG/ESO 2.2 m telescope at LSO and the 0.30 m Perth Exoplanet Survey Telescope (PEST) located in Perth, Australia. The observations are listed in Table 1, with the light curves plotted in Figs 2, 3 and 5.

Figure 3. Top: HATS551-019 radial velocities and the Keplerian orbit fit. ANU 2.3 m Echelle data are plotted as squares, and CORALIE data as triangles. Bottom: follow-up transit light curve and model fit.

Figure 4. HATS551-021 radial velocities and the Keplerian orbit fit. ANU 2.3 m Echelle data are plotted as squares, CORALIE data as triangles and FEROS data as circles.
of the GROND observing strategy and data reduction procedure can be found in Penev et al. (2013) and Mohler-Fischer et al. (2013).

2.4.3 PEST

A full transit of HATS553-001 and a partial transit of HATS551-019 were observed using PEST on 2012 December 22 and 23, respectively. PEST is a fully automated 0.30 m Meade LX200 Schmidt Cassegrain telescope located at latitude $-31^\circ 59' 34''$ and longitude $115^\circ 47' 53''$E. The telescope is coupled with a focal reducer to yield a focal ratio of f/5. The detector is an SBIG ST-8XME CCD camera with a gain of $2.27 e^- ADU^{-1}$ and read noise of $19.9 e^-$, and with image scale of 1.2 arcsec pixel$^{-1}$, and an FoV of 31 arcmin $\times$ 21 arcmin. Images were taken in the R$_g$ band, with the telescope in focus; exposure times are provided in Table 1. Typical conditions yield stellar point spread functions with full width at half-maximum $\sim$3 pixels. Flat-field frames were taken in twilight whenever possible. Dark frames of equal exposure length to the object frames were drawn from a library of master dark frames, renewed every month.

Image reduction and aperture photometry were performed using the C-Munipack program. Relative photometry is performed, with the reference light curve made from the weighted average of high S/N field star light curves.

3 ANALYSIS

3.1 Fundamental stellar atmospheric parameters

The fundamental primary star properties, including effective temperature ($T_{\text{eff}}$), surface gravity ($\log g$), metallicity ([Fe/H]) and projected rotational velocity ($v\sin i_0$), were derived by fitting synthetic model spectra to the averaged ANU 2.3 m/Echelle observations. We generated a synthetic spectral library with the ATLAS9 model atmospheres (Castelli & Kurucz 2004), using the spectral synthesis program SPECTRUM$^2$ (Gray & Corbally 1994). The spectra have resolutions of $R=24,000$, matching that of the Echelle instrument; they were generated at the ATLAS9 $T_{\text{eff}}$, $\log g$ and [Fe/H] grid points, using the default isotopic line lists provided with SPECTRUM, and then broadened to multiple rotational velocities spaced 5 km s$^{-1}$ apart. Model microturbulences are fixed at 2 km s$^{-1}$, given that the range of possible microturbulence values for the $T_{\text{eff}}$ and $\log g$ tested varies only by $\sim$0.5 km s$^{-1}$ (Husser et al. 2013). The individual echelle orders of the observed spectrum were matched to a restricted grid, centred about the rough stellar parameter estimates from the WiFeS spectrum. Using exposures of standard stars, we found echelle orders that gave the most reliable stellar parameters for a target of a given spectral type. The fitting results from these selected orders were weight averaged according to their rms scatter from the fit. The $\log g$ was subsequently constrained from theoretical isochrones (see Section 3.2) via global light curve and radial velocity modelling. We then performed the grid search again, at a finer $v\sin i_0$ grid of 1 km s$^{-1}$ spacings, with $\log g$ fixed, to obtain the final stellar parameters. The primary star parameters are presented in Table 3.

To investigate the errors in the spectral typing pipeline, we observed seven reference stars from Valenti & Fischer (2005), and four known planet hosting stars of similar spectral type and brightness to our candidates (WASP-61, 62, 78 and 79; Hellier et al. 2012; Smalley et al. 2012). These observations were used to determine

\footnote{http://www1.appstate.edu/dept/physics/spectrum/spectrum.html}
the echelle orders that yielded the most reliable spectral types. Reference stars with $v \sin i > 10$ km s$^{-1}$ were also analysed at the finer 1 km s$^{-1}$ $v \sin i_{\text{rot}}$ grid spacing. We are not sensitive to rotational velocities of $v \sin i < 10$ km s$^{-1}$, where we become limited by the instrument resolution. The rms differences between our measured stellar parameters and literature values are 113 K in $T_{\text{eff}}$, 0.19 dex in $\log g$, 0.12 dex in [Fe/H] and 4.4 km s$^{-1}$ in $v \sin i_{\text{rot}}$. After correcting for an empirical offset in each parameter, we get errors of 88 K in $T_{\text{eff}}$, 0.13 dex in $\log g$, 0.09 dex in [Fe/H] and 0.7 km s$^{-1}$ in $v \sin i_{\text{rot}}$. The offsets have been incorporated in the stellar parameters presented here.

Macro turbulence and microturbulence are free parameters in 1D stellar atmosphere models that contribute to the overall broadening of the spectral features. We investigate the degeneracy between these parameters and the measured stellar rotational broadening. The spectrum of HATS550-016 was fitted to synthetic spectral grids generated at macro- and microturbulences from 0 to 5 km s$^{-1}$, producing a mean variation of 0.8 km s$^{-1}$ in the resulting $v \sin i_{\text{rot}}$ measurement, smaller than our quoted measurement errors. Since the rotational broadening parameter for all host stars studied is much larger than the broadening from macro- and microturbulence, we conclude minimal systematic uncertainty contributions from these parameters. In addition, we checked for the dependence of the measured $v \sin i_{\text{rot}}$ to the synthetic spectral resolution and found a variation of 0.6 km s$^{-1}$ over a change in resolution of 1000. Since the resolution is measured from the ThAr arc lamp spectra, we expect no significant contribution from uncertainties in the resolution to the $v \sin i_{\text{rot}}$ systematic uncertainties.

3.2 Global modelling of data

To derive the system properties, we performed simultaneous modelling of the HATSouth discovery photometry, follow-up photometry where available and radial velocity measurements. The light curves were modelled using the Nelson & Davis (1972) model for eclipsing binaries, allowing for ellipsoidal phase variations, as implemented in the JKTEBOP code (Popper & Etzel 1981; Southworth, Maxted & Smalley 2004). The Keplerian orbit was used to model the radial velocity measurements.

The free parameters in the global fit include the orbital period $P$, transit time $T_{\text{trans}}$, radius ratio $R_2/R_1$, normalized radius sum $R_{\text{sum}} = (R_1 + R_2)/a$, radial velocity orbit semi-amplitude $K$, eccentricity parameters $e \cos \omega$ and $e \sin \omega$, and inclination $i$. Quadratic limb darkening coefficients for the primary star were fixed to values as from Claret (2000). We assume uniform priors for all the free parameters. In the cases where the proposed iteration in inclination is $i > 90^\circ$, we adopt the $180^\circ - i$ geometry to avoid the discontinuous boundary. To account for the non-zero flux contribution from the M-dwarf companion, we also obtain an approximate surface brightness estimate for the companion using a 5 Gyr Baraffe et al. (1998) isochrone. However, the flux contribution from the M-dwarf is $\ll$0.1 percent in the $R$ band and is negligible. Ellipsoidal variations are included in the model by including the mass ratio parameter $q$, using masses determined per iteration from isochrone fitting (see Section 3.3.1). The best-fitting parameters and the surrounding error space were explored by the emcee (Foreman-Mackey et al. 2013) implementation of a Markov chain Monte Carlo (MCMC) ensemble sampler, with the individual measurement errors for all data sets (discovery, follow-up photometry and radial velocity) inflated such that the reduced $\chi^2$ is at unity.

Instrumental offsets were derived for each instrument separately. In addition, the HATSouth discovery light curves can be diluted in eclipse depth if they are treated by the TFA detrending algorithm. In the cases where well-sampled follow-up photometry is available (HATS550-016 and HATS553-001), we fitted for a dilution factor for the HATSouth light curves, using the follow-up light curve as reference. Where follow-up photometry of the full transit is not available (HATS551-019 and HATS551-021), simultaneous TFA corrections were performed on the HATSouth light curve using the transit model for each MCMC iteration (see section 6, Kovács et al. 2005).

3.3 Determination of mass and radius

We derive the mass and radius of the primary and secondary stars at each iteration via (1) determination of the primary star properties from stellar isochrones using measured spectroscopic and light curve parameters, (2) assuming spin–orbit synchronization for

| Property | HATS550-016 | HATS551-019 | HATS551-021 | HATS553-001 |
|----------|-------------|-------------|-------------|-------------|
| GSC$^a$  | 6465-00602  | 6493-00290  | 6493-00315  | 5946-00892  |
| RA$^b$ (J2000 HH:MM:SS.SS) | 04:48:23.32 | 05:40:46.16 | 05:42:49.12 | 06:16:00.66 |
| DEC$^b$ (J2000 DD:MM:SS.SS) | $-24:50:16.88$ | $-24:55:35.16$ | $-25:59:47.49$ | $-21:15:23.82$ |

Photometric properties

| Property | HATS550-016 | HATS551-019 | HATS551-021 | HATS553-001 |
|----------|-------------|-------------|-------------|-------------|
| $V$      | 13.605 ± 0.041 | 12.058 ± 0.006 | 13.114 ± 0.008 | 13.189 ± 0.021 |
| $B$      | 14.052 ± 0.020 | 12.497 | 13.580 ± 0.012 | 13.694 ± 0.014 |
| $g^c$    | 13.782 ± 0.032 | 12.198 | 13.308 | 13.408 |
| $r^c$    | 13.499 ± 0.031 | 11.953 | 13.044 | 13.102 |
| $i^c$    | 13.438 | 11.922 ± 0.038 | 12.985 ± 0.077 | 13.988 |
| $J$      | 12.640 ± 0.021 | 11.146 ± 0.021 | 12.150 ± 0.021 | 12.245 ± 0.021 |
| $H$      | 12.379 ± 0.025 | 10.943 ± 0.024 | 11.956 ± 0.020 | 12.023 ± 0.025 |
| $K$      | 12.308 ± 0.021 | 10.914 ± 0.021 | 11.873 ± 0.023 | 11.970 ± 0.024 |

Derived spectroscopic properties

| Property | HATS550-016 | HATS551-019 | HATS551-021 | HATS553-001 |
|----------|-------------|-------------|-------------|-------------|
| $T_{\text{eff}}$ (K) | 6420 ± 90 | 6380 ± 170 | 6670 ± 220 | 6230 ± 250 |
| [Fe/H]    | $-0.60 ± 0.06$ | $-0.4 ± 0.1$ | $-0.4 ± 0.1$ | $-0.1 ± 0.2$ |
| $v \sin i_{\text{rot}}$ (km s$^{-1}$) | 30.0 ± 1.7 | 17.1 ± 2.0 | 16.4 ± 10.6 | 22.2 ± 1.8 |

$^a$Hubble guide star catalogue.

$^b$2MASS.

$^c$APASS Data Release 7, uncertainties are quoted where available as the scatter from multiple observations.
the system and deriving mass and radius from the spectroscopic \(v \sin i_{\text{rot}}\) measurement, and (3) a combined analysis that includes isochrone fitting and the assumption of spin–orbit synchronization. Each analysis employs a separate MCMC routine that explores their respective posteriors.

### 3.3.1 Isochrone fitting

Sozzetti et al. (2007) showed that the normalized orbital distance \(a/R_1\), derived from the global fit, can be combined with model isochrones to refine the stellar atmosphere parameters. \(a/R_1\) is related to the mean stellar density by

\[
\frac{M_1}{R_1^3} = \frac{4\pi^2}{GP^2} \left( \frac{a}{R_1} \right)^3 - \frac{M_2}{R_2^3}.
\]

(1)

Although the second term is usually insignificant and often discarded in the case of transiting planets, it cannot be ignored for stellar mass companions (Triaud et al. 2013). Therefore, for each iteration of the minimization and MCMC routines, we used initial estimates of \(M_1\) and \(R_1\) to derive \(M_2\) from the radial velocity orbit, then used the \(M_2\) estimate and the fitted \(a/R_1\) and spectroscopically determined \(T_{\text{eff}}\) and \([\text{Fe/H}]\) to derive new theoretical \(M_1\) and \(R_1\) values from isochrone fitting. Finally, the new primary mass and radius were used to derive a refined \(M_2\) estimate. The Yonsei-Yale isochrones (Yi et al. 2001) provide the theoretical stellar masses and radii. To incorporate the uncertainties in the spectroscopic stellar parameters into the error analysis, \(T_{\text{eff}}\) and \([\text{Fe/H}]\) were drawn from Gaussian distributions in the MCMC routine. This method also gives us a more precise estimate for \(\log g\) of the primary star. This \(\log g\) value was incorporated into the spectral classifications process (Section 3.1) to better constrain the \(T_{\text{eff}}\), \([\text{Fe/H}]\) and \(v \sin i_{\text{rot}}\) estimates.

### 3.3.2 Spin–orbit synchronization

For stellar mass binaries at short periods, spin–orbit synchronization via tidal interactions is expected to occur within \(~100\) myr (Zahn 1977; Hut 1981). If we assume spin–orbit synchronization for these systems and that the stellar spin-axis is near perpendicular to our line of sight \(i_{\text{orb}} = i_{\text{act}}\), then it is also possible to derive model-independent estimates of the stellar masses and radii (e.g. Beatty et al. 2007). The masses and radii of components A and B can be calculated from purely observable quantities using

\[
M_1 = \frac{P}{2\pi G} \left( \frac{a}{R_1} \right)^2 (v \sin i_{\text{rot}})^2 \times \left[ \frac{(a/R_1) \sin i_{\text{rot}} - K \sqrt{1 - e^2}}{\sin^3 i_{\text{orb}}} \right]
\]

(2)

\[
M_2 = \frac{P}{2\pi G} \left( \frac{a}{R_1} \right)^2 \frac{K(v \sin i_{\text{rot}})^2 \sqrt{1 - e^2}}{\sin^3 i_{\text{orb}}}
\]

(3)

\[
R_1 = \frac{P \, v \sin i_{\text{rot}}}{2\pi \sin i_{\text{orb}}}
\]

(4)

\[
R_2 = R_1 \left( \frac{R_2}{R_1} \right)
\]

(5)

We caution that spin–orbit synchronization and the alignment of the stellar spin-axis should not be automatically assumed. Although rapid synchronization is expected for binary systems, some previous F-M binaries have been measured to be asynchronous (e.g. Pont et al. 2005, 2006; Triaud et al. 2013). In addition, whilst the alignment of the stellar spin and companion orbital axes is also often predicted from formation and tidal interactions (and by extension of the transit geometry the stellar spin-axis should also be perpendicular to our line of sight) spin–orbit misaligned stellar binaries have been identified (DI Her, KOI-368; Albrecht et al. 2009; Zhou & Huang 2013). It is therefore necessary to compare the stellar parameter results from synchronization against that of isochrone fitting before this method can be adopted.

For each iteration of the global minimization and MCMC routine, we also calculated the primary and companion masses and radii assuming synchronization. The adopted \(v \sin i_{\text{rot}}\) value was given by the spectroscopic analysis and was drawn from a Gaussian distribution in the MCMC error analysis.

### 3.3.3 Combined mass–radius estimate

We also perform a combined analysis, where the mass and radius are calculated using isochrone fitting as described in Section 3.3.1. The expected \(v \sin i_{\text{rot}}\) is then derived using the period and radius, and compared to the measured \(v \sin i_{\text{rot}}\). We calculate an additional \(\chi^2\) term,

\[
\chi^2_{v \sin i_{\text{rot}}} = \frac{2\pi R_1 \sin i_{\text{rot}}}{P - v \sin i_{\text{rot}}} \frac{\Delta v \sin i_{\text{rot}}}{\Delta v \sin i_{\text{rot}}}
\]

(6)

which is added to the \(\chi^2\) from the light curve and radial velocity data. Due to the transit geometry, we approximate \(\sin i_{\text{orb}} \approx 1\) in the calculation. The MCMC minimization is rerun for this combined analysis.

The probability distributions for the mass and radius, measured using the above techniques, are plotted in Fig. 6. We find that the 2σ confidence regions derived using isochrone and synchronization overlap for all the systems. This indicates that the assumption of spin–orbit synchronization, required for the combined analysis (Section 3.3.3), is valid for all systems. The system parameters from the combined analysis is adopted for discussion here onwards. The stellar and system parameters are presented in Table 4.

We also tested the sensitivity of the final results against various assumptions in the methods outlined above. These tests were performed on the HATS550-016 data set. The limb darkening coefficients were set free and allowed to vary within 0.2 of the values from Claret (2000). The resulting system parameters did not deviate from those presented in Table 4, with no significant increase in the uncertainties. To test the dependence of the results on the Yonsei-Yale isochrones, we performed the analysis in Section 3.3.1 using the Dartmouth isochrones (Dotter et al. 2008) but found no deviation in the results. To test the effectiveness of reconstructive TFA (Kovács et al. 2005) at recovering the true transit shape, we analysed the HATS550-016 system using only the HATSouth discovery data by excluding the follow-up photometry observations and found no significant deviation in the results; however, the uncertainties were increased by a factor of \(~2–3\). We caution that correlated noise, present in the follow-up light curve, was unaccounted for in the analysis and may lead to underestimated uncertainties.

### 4 DISCUSSION

We have presented the discovery of four transiting VLMSs, with masses ranging from 0.1 to 0.2 M\(\odot\). Their properties are discussed briefly below.
Table 4. Properties of the HATSouth transiting VLMS systems.

| Parameter   | HATS550-016 | HATS551-019 | HATS551-021 | HATS553-001 |
|-------------|-------------|-------------|-------------|-------------|
| Fitted parameters |
| $P$ (d)     | 2.051 811±0.000 012 | 4.686 813±0.000 012 | 3.636 378±0.000 005 | 3.804 053±0.000 001 |
| $T_0$ (HJD) | 245 5104.286±0.001 | 245 5474.179±0.001 | 245 5087.426±0.002 | 245 5093.563±0.001 |
| $R_{\text{sum}}$ | 0.196±0.003 | 0.149±0.006 | 0.131±0.004 | 0.158±0.005 |
| $R_2/R_1$   | 0.1205±0.0003 | 0.107±0.002 | 0.124±0.003 | 0.136±0.003 |
| $i$ (°)     | 90±1° | 85±1° | 90±1° | 83.4±0.4° |
| $e \cos \omega$ | −0.001±0.002 | −0.003±0.002 | −0.003±0.002 | 0.0003±0.002 |
| $e \sin \omega$ | 0.08±0.02 | 0.04±0.02 | 0.06±0.02 | 0.03±0.02 |
| $K$ (km s$^{-1}$) | 17.2±0.4 | 18.4±0.7 | 16.2±0.2 | 20.9±0.9 |
| Derived parameters |
| $\log g$     | 4.25±0.02 | 4.01±0.05 | 4.30±0.04 | 4.13±0.05 |
| Age (Gyr)    | 5±1 | 6±2 | 4±3 | 3±2 |
| $M_1$ (M$_\odot$) | 0.97±0.05 | 1.10±0.05 | 1.1±0.1 | 1.2±0.1 |
| $R_1$ (R$_\odot$) | 1.22±0.02 | 1.70±0.09 | 1.20±0.08 | 1.58±0.08 |
| $M_2$ (M$_\odot$) | 0.110±0.005 | 0.17±0.01 | 0.132±0.014 | 0.20±0.02 |
| $R_2$ (R$_\odot$) | 0.147±0.004 | 0.18±0.01 | 0.154±0.008 | 0.22±0.01 |

Figure 6. The 1σ and 2σ confidence regions for the masses and radii of the VLMS systems presented in this study. We plot individual confidence regions derived from the isochrone fit (blue), assuming spin–orbit synchronization (red) and the combined analysis (grey). The confidence regions from the combined analysis is adopted. The corresponding crosses mark the peak of the probability distributions.
4.1 HATS550-016B
HATS550-016B is the lowest mass star within our sample and is the second lowest mass star known with mass and radius determined to better than 10 per cent (after J1219-39b; Triau et al. 2013). It has a mass and radius of $0.110^{+0.006}_{-0.005} \, M_\odot$ and $0.147^{+0.009}_{-0.008} \, R_\odot$, and orbits a relatively metal deficient ([Fe/H] = $-0.60 \pm 0.06$) F-type star of age $5.1^{+1.0}_{-0.5}$ Gyr in a period of $2.051^{+0.00002}_{-0.00002}$ days. The radius of HATS550-016B is inflated by 13 per cent compared to Baraffe et al. (1998) models, assuming that it has the same metallicity as the primary star. It is the only star in this sample that is inflated with respect to the isochrones.

4.2 HATS551-019B
HATS551-019B is a $0.17^{+0.01}_{-0.01} \, M_\odot$, $0.19^{+0.01}_{-0.01} \, R_\odot$ VLMS with a $4.686^{+0.002}_{-0.000} \, d$ period orbit about a $6^{+2}_{-2} \, Gyr$ F subgiant, with a subsolar metallicity of [Fe/H] = $-0.4 \pm 0.1$. Since the follow-up photometry of HATS551-019B covers only the egress event, the HATSouth discovery light curves, detrended using simultaneous TFA, are also used to constrain the $R_2/R_1$ ratio. The radius of HATS551-019B agrees with theoretical predictions to within errors.

4.3 HATS551-021B
HATS551-021B is a $0.132^{+0.014}_{-0.007} \, M_\odot$, $0.154^{+0.006}_{-0.008} \, R_\odot$ VLMS in a $3.636^{+0.00005}_{-0.00005} \, d$ period orbit about an F dwarf with a metallicity of [Fe/H] = $-0.4 \pm 0.1$. The age of the primary star is ill defined from isochrone fitting ($4^{+3}_{-2}$ Gyr). We find no chromospheric Ca H&K emission nor excess Li absorption, indicating that the system is likely >1 Gyr in age. No follow-up photometry is available for HATS551-021, so the $R_2/R_1$ ratio is constrained purely from HATSouth discovery light curves. The radius of HATS551-021B matches theoretical isochrones very well.

4.4 HATS553-001B
HATS553-001B is a VLMS with $0.20^{+0.01}_{-0.02} \, M_\odot$, and radius of $0.22^{+0.01}_{-0.01} \, R_\odot$, orbiting a $3^{+2}_{-2} \, Gyr$ F-type star of near solar metallicity ([Fe/H] = $-0.1 \pm 0.2$) in a $3.804^{+0.0001}_{-0.0001} \, d$ period orbit. The radius of HATS553-001B matches the isochrones to within errors.

4.5 Mass–radius relationship
The masses and radii of the VLMS companions presented in this paper, as well as that of known well-studied VLMSs (Table 5), are plotted in Fig. 7. Of the VLMSs reported in this study, we find only HATS550-016B to be inflated compared to theoretical isochrones; HATS551-019B, HATS551-021B and HATS553-001B, agree with the isochrone mass–radius relations to within measurement uncertainties.

Table 5. Properties of known VLMSs.

| Object | Mass ($M_\odot$) | Radius ($R_\odot$) | Method | [Fe/H] | Period (d) | $T_{\text{eff}}$ (K) | Companion $T_{\text{eff}}$ (K) | Reference |
|--------|----------------|-------------------|--------|--------|-------------|----------------------|-----------------------------|-----------|
| F-G-M Binaries $^a$ | | | | | | | | |
| HAT-TR-205-013B | $0.124 \pm 0.01$ | $0.167 \pm 0.006$ | SB1, synchronization $^b$ | $-0.0 \pm 0.5$ | 2.23 | 6295 ± 200 | Beatty et al. (2007) |
| J1219-39B | $0.091 \pm 0.002$ | $0.1174^{+0.0073}_{-0.0073}$ | SB1, isochrone $^c$ | $-0.209 \pm 0.072$ | 6.76 | 5400 ± 90 | Triau et al. (2013) |
| KIC 1571511B | $0.141^{+0.004}_{-0.0012}$ | $0.1783^{+0.0013}_{-0.0018}$ | SB1, isochrone | $0.37 \pm 0.08$ | 14.02 | 6195 ± 50 | Ofir et al. (2012) |
| T-Lyr-08070B | $0.240 \pm 0.019$ | $0.265 \pm 0.010$ | SB1, synchronization | $-0.9^c$ | 1.18 | 6250 ± 140 | Fernandez et al. (2009) |
| T-Lyr-01662B | $0.198 \pm 0.012$ | $0.238 \pm 0.007$ | SB1, synchronization | $-0.9^c$ | 4.23 | 6200 ± 200 | Fernandez et al. (2009) |
| K, M-M Binaries | | | | | | | | |
| CM Dra A | $0.2130 \pm 0.0009$ | $0.2534 \pm 0.0019$ | SB2 $^d$ | $-0.3 \pm 0.12$ | 1.27 | 3130 ± 70 | 3120 ± 70 | Morales et al. (2009) |
| CM Dra B | $0.2141 \pm 0.0010$ | $0.2396 \pm 0.0015$ | SB2 | $-0.3 \pm 0.12$ | 1.27 | 3120 ± 70 | 3130 ± 70 | Morales et al. (2009) |
| Kepler-16B | $0.2025^{+0.0016}_{-0.0016}$ | $0.2263^{+0.0039}_{-0.0035}$ | SB1, photodynamical $^e$ | $-0.3 \pm 0.2$ | 41.08 | 4450 ± 150 | Doyle et al. (2011) |
| KOI-126B | $0.2413 \pm 0.003$ | $0.2543 \pm 0.0014$ | SB1, photodynamical | $0.15 \pm 0.08$ | 1.77 | 5875 ± 100 | Carter et al. (2011) |
| (About KOI-126C) | | | | | | | | |
| (About KOI-126A) | | | | | | | | |
| KOI-126C | $0.2127 \pm 0.0026$ | $0.2318 \pm 0.0013$ | SB1, photodynamical | $0.15 \pm 0.08$ | 1.77 | 5875 ± 100 | Carter et al. (2011) |
| (About KOI-126B) | | | | | | | | |
| (About KOI-126A) | | | | | | | | |
| Single Stars | | | | | | | | |
| GJ 191 | $0.281 \pm 0.014$ | $0.291 \pm 0.025$ | Interferometry | $-0.99 \pm 0.04$ | 3570 ± 160 | Séguransan et al. (2003) |
| GJ 551 | $0.123 \pm 0.006$ | $0.141 \pm 0.007$ | Interferometry | $0.21 \pm 0.03^b$ | 3098 ± 56 | Séguransan et al. (2003) |
| GJ 699 | $0.146 \pm 0.015$ | $0.1867 \pm 0.0002$ | Interferometry | $-0.39 \pm 0.17$ | 3224 ± 10 | Séguransan et al. (2003) |

$^a$With 0.08 < $M$ < 0.3 $M_\odot$, mass and radius measured to better than 10 per cent precision and valid [Fe/H] measurements.

$^b$Assume primary star [Fe/H].

$^c$SB1, synchronization: single-lined stellar binary, parameters derived from assuming spin–orbit synchronization.

$^d$SB1, isochrone: single-lined stellar binary, parameters derived from isochrone fitting.

$^e$[Fe/H] adopted from table 13 of Fernandez et al. (2009), by finding the best-matching results between the isochrone and synchronization techniques. We assume an error of 0.5 dex (grid size) in our analysis of BIC and F-test.

$^f$SB2: double-lined eclipsing binary, parameters determined dynamically.

$^g$SB1, photodynamical: global analysis of single-lined radial velocity data and light-curve transit timing variations for multi-body systems.

$^h$Adopting [Fe/H] of $\alpha$ Centauri A, see Johnson & Apps (2009).
We tested for any general radius deviation between the observed VLMS population and the isochrones. The theoretical radii are taken from the 5 Gyr isochrones from Baraffe et al. (1998), interpolated between [M/H] = −0.5 and 0.0, and linearly extrapolated beyond when necessary, to account for the metallicity dependence. For each object, we sample the isochrones via a Monte Carlo analysis, drawing mass and metallicity values from Gaussian distributions about the measured values and their associated uncertainties, and derive a predicted model radius and uncertainty. For this discussion on the radius deviation between model and measurements, we adopted the radius uncertainty as the quadrature addition of the uncertainties in the measurement and model sampling.

We also note that the difference between the Baraffe et al. (1998) and the Dartmouth isochrones (Dotter et al. 2008) is minor compared to the deviation from observations (see green isochrone lines in Fig. 7); hence, the following calculations were performed relative to the Baraffe et al. (1998) isochrones only. In addition, we also explored isochrones of younger ages and shorter mixing length using the Baraffe et al. (1998) isochrones; neither factors have obvious effects at this mass range.

The $\chi^2$ of the observed population is compared to (Model A) the isochrones without modification and (Model B) with isochrone radii inflated by 1.05. If the $\chi^2$ is calculated with the measurement uncertainties taken at face value, the Bayesian information criterion (BIC) between the two models is 50 ($\chi^2$/dof = 7 and 3, for Models A and B, respectively), tentatively favouring an inflation of radius from the isochrones. The F-test for the variance ratio of the fit to the two models gives a $p$-value of 0.08, suggesting a very tentative preference towards Model B. Both BIC and the $F$-test account for the greater complexity of Model B over A. A number of studies (Morales et al. 2010; Windmiller, Oroz & Etzel 2010; Feiden & Chaboyer 2012) have commented that the presence of spots can impose radii uncertainties of the order of 2 per cent in these measurements. After imposing a minimum radius uncertainty of 2 per cent on the same population, we find BIC = 21 ($\chi^2$/dof = 3 and 2, for Models A and B, respectively) and $F$-test $p$-value of 0.11. The $F$-test result, after inflating the uncertainties, suggests no real preference between Models A and B. In addition, 5 per cent systematic deviation between measurements and model is significantly smaller than the ~10 per cent stated by earlier studies (e.g. Ribas 2006) and agrees with more recent studies of higher mass double-lined M-dwarf binaries, using newer isochrone sets (e.g. Kraus et al. 2011; Feiden & Chaboyer 2012; Spada et al. 2013).

The rms scatter of observed — theoretical stellar radius difference (3 per cent) is slightly larger than the mean observational uncertainties (5 per cent). Whilst this is likely due to the underestimated observational uncertainties, it may also point towards secondary factors, beyond mass and metallicity, that affect the radii of VLMSs. Fig. 8 plots the radius discrepancy against mass, orbital period and incident flux from the primary star. For each factor, the Pearson correlation coefficient $r$ is calculated, weighted by the measurement uncertainties, with the radius uncertainties of M-M binaries increased to 2 per cent. We find no significant correlation with any of these parameters.

In particular, activity-induced inflation of the stellar radius should be correlated with shorter period if faster rotation gives rise to more powerful internal dynamos (López-Morales 2007). This is not observed in the low-mass population. However, it is not obvious that we expect such period–activity–radius dependences, since the dynamos in fully convective stars may operate differently to
The observed – theoretical radius difference of the VLMSs are correlated.

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APPENDIX A: LIGHT-CURVE AND RADIAL VELOCITY DATA

Tables A1–A4 present the discovery and follow-up light-curve data for the objects presented in this study. Tables A5–A8 present the associated radial velocity data.

Table A1. Differential photometry for HATS550-016.

| BJD-240 0000 | Flux | ∆Flux | Instrument | Filter |
|--------------|------|-------|------------|--------|
| 551 03.463 354 | 0.987 94 | 0.010 25 | HS | ✓ |
| 551 03.479 516 | 1.002 49 | 0.010 28 | HS | ✓ |
| 551 03.485 975 | 1.022 98 | 0.009 73 | HS | ✓ |
| 551 04.721 430 | 0.991 44 | 0.007 34 | HS | ✓ |
| 551 30.407 508 | 0.992 68 | 0.008 48 | HS | ✓ |

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.

Table A2. Differential photometry for HATS551-019.

| BJD-240 0000 | Flux | ∆Flux | Instrument | Filter |
|--------------|------|-------|------------|--------|
| 550 83.758 920 | 1.002 76 | 0.003 11 | HS | ✓ |
| 550 83.762 160 | 1.000 41 | 0.003 05 | HS | ✓ |
| 550 83.765 520 | 1.002 70 | 0.003 03 | HS | ✓ |
| 550 83.768 730 | 0.995 39 | 0.002 98 | HS | ✓ |
| 550 83.772 100 | 1.002 67 | 0.002 96 | HS | ✓ |

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.

Table A3. Differential photometry for HATS551-021.

| BJD-240 0000 | Flux | ∆Flux | Instrument | Filter |
|--------------|------|-------|------------|--------|
| 550 83.758 920 | 0.979 41 | 0.005 66 | HS | ✓ |
| 550 83.762 160 | 0.992 82 | 0.005 77 | HS | ✓ |
| 550 83.765 520 | 0.978 66 | 0.005 72 | HS | ✓ |
| 550 83.768 730 | 0.980 86 | 0.005 69 | HS | ✓ |
| 550 83.772 100 | 0.982 39 | 0.005 83 | HS | ✓ |

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.

Table A4. Differential photometry for HATS553-001.

| BJD-240 0000 | Flux | ∆Flux | Instrument | Filter |
|--------------|------|-------|------------|--------|
| 550 91.519 969 | 0.986 37 | 0.005 68 | HS | ✓ |
| 550 91.523 285 | 0.990 27 | 0.005 33 | HS | ✓ |
| 550 91.526 738 | 0.995 89 | 0.005 28 | HS | ✓ |
| 550 91.530 049 | 0.994 46 | 0.005 22 | HS | ✓ |
| 550 91.533 508 | 0.986 95 | 0.005 12 | HS | ✓ |

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.
Table A5. Radial velocities for HATS550-016.

| BJD-240 0000 | RV (km s$^{-1}$) | ΔRV (km s$^{-1}$) | Instrument |
|--------------|------------------|------------------|------------|
| 561 64.877 923 | 21.49            | 0.08             | CORALIE    |
| 562 37.817 487 | 5.81             | 0.08             | CORALIE    |
| 562 38.819 306 | 16.33            | 0.08             | CORALIE    |
| 562 39.850 619 | 6.69             | 0.08             | CORALIE    |
| 562 41.679 708 | −3.25            | 0.08             | CORALIE    |

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.

Table A6. Radial velocities for HATS551-019.

| BJD-240 0000 | RV (km s$^{-1}$) | ΔRV (km s$^{-1}$) | Instrument |
|--------------|------------------|------------------|------------|
| 554 97.745 634 | 10.14            | 0.04             | CORALIE    |
| 556 08.701 137 | 33.44            | 0.04             | CORALIE    |
| 556 10.699 243 | −0.51            | 0.05             | CORALIE    |
| 563 74.907 520 | −7.46            | 0.61             | ANU2.3 m/ECHELLE |
| 563 75.887 520 | 4.32             | 0.56             | ANU2.3 m/ECHELLE |

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Table A7. Radial velocities for HATS551-021.

| BJD-240 0000 | RV (km s$^{-1}$) | ΔRV (km s$^{-1}$) | Instrument |
|--------------|------------------|------------------|------------|
| 554 97.766 487 | 28.16            | 0.06             | CORALIE    |
| 556 08.553 710 | −1.30            | 0.07             | CORALIE    |
| 556 10.627 251 | 26.18            | 0.06             | CORALIE    |
| 558 13.836 900 | 28.69            | 0.28             | FEROS      |
| 558 14.854 700 | 8.32             | 0.25             | FEROS      |

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Table A8. Radial velocities for HATS553-001.

| BJD-240 0000 | RV (km s$^{-1}$) | ΔRV (km s$^{-1}$) | Instrument |
|--------------|------------------|------------------|------------|
| 563 74.955 480 | 26.75            | 0.80             | ANU2.3 m/ECHELLE |
| 563 75.925 980 | −3.30            | 0.71             | ANU2.3 m/ECHELLE |
| 563 77.923 100 | 25.50            | 0.74             | ANU2.3 m/ECHELLE |
| 563 78.918 650 | 23.46            | 0.73             | ANU2.3 m/ECHELLE |
| 563 80.938 390 | −2.56            | 1.24             | ANU2.3 m/ECHELLE |

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.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table A1. Differential photometry for HATS550-016.
Table A2. Differential photometry for HATS551-019.
Table A3. Differential photometry for HATS551-021.
Table A4. Differential photometry for HATS553-001.
Table A5. Radial velocities for HATS550-016.
Table A6. Radial velocities for HATS551-019.
Table A7. Radial velocities for HATS551-021.
Table A8. Radial velocities for HATS553-001. (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt2100/-/DC1).

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