HAT-South and HAT-11B: Two Transiting Hot Jupiters Orbiting Subsolar Metallicity Stars Selected for the K2 Campaign 7

M. Rabus1,2, A. Jordán1, J. D. Hartman3, G. Á. Bakos3, N. Espinoza1, R. Brah1, K. Penev1, S. Cicerê2, G. Zhou4, D. Bayliss4,5, L. Mancini2, W. Bhatti3, M. de Val-Borro3, Z. Csillery3, B. Sato6, T.-G. Tan7, T. Henning3, B. Schmidt4, J. Bento4, V. Suci1, R. Noyes8, J. Lázár9, I. Papp9, and P. Sár19

1 Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 7820436 Macul, Santiago, Chile; mrabus@astro.puc.cl
2 Department of Astrophysical Sciences, Princeton University, NJ 08544, USA
3 Department of Astrophysical Sciences, Princeton University, NJ 08544, USA
4 Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
5 Observatoire Astronomique de l’Université de Genève, 51ch. des Maillettes, 1290 Versoix, Switzerland
6 Department of Earth and Planetary Sciences, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8551, Japan
7 Perth Exoplanet Survey Telescope, Perth, Australia
8 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
9 Hungarian Astronomical Association, Budapest, Hungary

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ABSTRACT

We report the discovery of two transiting extrasolar planets from the HATSouth survey. HAT-South is a periodic 12.9 mmag dip in its light curve every 3.6192 days and a radial velocity variation consistent with a Keplerian orbit. HAT-South has a mass of 1.00 ± 0.060 M_J, a radius of 1.444 ± 0.057 R_J, and an effective temperature of 6060 ± 150 K, while its companion is a 0.85 ± 0.12 M_J, 1.510 ± 0.078 R_J planet in a circular orbit. HAT-12 shows a periodic 5.1 mmag flux decrease every 3.1428 days and Keplerian RV variations around a V = 12.8 F-star. HAT-12 has a mass of 1.489 ± 0.071 M_J, a radius of 2.21 ± 0.21 R_J, and an effective temperature of 6408 ± 75 K. For HAT-South, our measurements indicate that this is a 2.38 ± 0.11 M_J, 1.35 ± 0.17 R_J planet in a circular orbit. Both host stars show sub-solar metallicities of −0.390 ± 0.060 dex and −0.100 ± 0.040 dex, respectively, and are (slightly) evolved stars. In fact, HAT-11 is among the most metal-poor and, HAT-12, with a log g of 3.923 ± 0.065, is among the most evolved stars hosting a hot-Jupiter planet. Importantly, HAT-11 and HAT-12 have been observed in long cadence by Kepler as part of K2 campaign 7 (EPIC 216414930 and EPIC 218131080 respectively).

Key words: planetary systems – stars: individual (HAT-South – HAT-12) – techniques: photometric – techniques: spectroscopic

Supporting material: machine-readable table

1. INTRODUCTION

Transiting Extrasolar Planets, hereafter TEPs, allow us to measure many of their physical properties that are not accessible for non-transiting systems and thus occupy a prominent place among the nearly 2000 exoplanets currently known.

One of the most important features of TEPs is that their radii can be measured from the transit shape if the radii of the stellar hosts are known. The radius, coupled with the measurement of the planetary mass from radial velocity (RV) observations, allows the computation of the bulk density of the planet and the possibility of inferring properties about its internal structure and composition.

The detection of close-in extrasolar giant planets has led to several theoretical challenges regarding their structure, formation, and subsequent evolution. One of the earliest realized challenges, and one that is yet to be solved, is the fact that close-in giant exoplanets often show radii that are far larger than those predicted by theories of giant planet evolution (e.g., HAT-P-32b Hartman et al. 2011). Moving forward in understanding the inflation mechanism will benefit from having larger samples of close-in, inflated gas giants, especially systems lying at some extreme of either planetary or stellar properties (Lopez & Fortney 2016).

One of the most basic properties one can measure of a star is its metallicity, and much attention in the past has been given to the dependence of planet occurrence rate on the host star metallicity. Several studies have found that gas giants appear more frequently around metal-rich stars, both from RV programs (Santos et al. 2004; Valenti & Fischer 2005; Johnson et al. 2010) and from Kepler data (Schlaufman & Laughlin 2011; Buchhave et al. 2012; Everett et al. 2013; Wang & Fischer 2015). Discoveries of gas giants around metal-poor stars then add systems to a region of parameter space that is intrinsically less populated. Furthermore, different physical scenarios have been brought forward to explain the metallicity–frequency correlation. Ida & Lin (2005) proposed that giant planets are preferentially formed around metal-rich stars by core accretion; whereas, other investigations from, e.g., Sandquist et al. (1998, 2002), Murray & Chaboyer (2002), and Pasquini et al. (2007) argue for a pollution of the host star by infalling planets. These two scenarios can be tested by comparing the population of planet bearing stars with accurately known characteristics.
In this work, we present two new inflated hot Jupiters orbiting metal-poor stars discovered by the HATSouth survey: HATS-11b and HATS-12b. The structure of the paper is as follows. In Section 2, we summarize the detection of the photometric transit signal and the subsequent spectroscopic and photometric observations of each star to confirm the planets. In Section 3, we analyze the data to rule out false positive scenarios and characterize the star and planet. In Section 4, we put our new systems in the context of the sample of the well characterized TEPs known to date.

2. OBSERVATIONS

2.1. Photometric Detection

The initial images of HATS-11 and HATS-12 were obtained with the HATSouth wide-field telescope network consisting of 24 Takahashi E180 astrophotographs with an aperture of 18 cm. The photons were detected with Apogee 4k × 4k U16M ALTA CCDs. Details on the time span and number of images are shown in Table 1. These images were processed following Penev et al. (2013). The light curves were trend-filtered following Kovács et al. (2005) and searched for periodic box-shaped signals using the box least-squares (Kovács et al. 2002) method. For HATS-11 (2MASS J19173618−2223236; \( \alpha = 19^h17^m36^s24, \delta = -22^\circ23'23''77; J2000; V = 14.018 \pm 0.081 \)) the discovery light curve showed a photometric precision between 10 and 14 mmag per point and the BLS algorithm detected a dip of 12.9 mmag every 3.6192 days. For the brighter HATS-12 star (2MASS J19164857−1921212; \( \alpha = 19^h16^m48^s72, \delta = -19^\circ21'21''2; J2000; V = 12.756 \pm 0.021 \)) the precision was between 6 and 7 mmag per point and a periodic flux decrease of 5.1 mmag with \( P = 3.1428 \) days was found, making this the third shallowest ground-based discovery to date, after HAT-P-11 (4.2 mmag, Bakos et al. 2010) and WASP-73 (3.6 mmag, Delrez et al. 2014). Both light curves are shown in Figure 1 and the numerical data is available in Table 3. These initial detections triggered further spectroscopic and photometric follow-up observations in order to confirm the transit and the planetary nature as explained in the following sections.

2.2. Spectroscopic Observations

We started observing both candidates spectroscopically, in a process that is split into two kinds of spectroscopic observations. A first step of reconnaissance spectroscopy serves to reject possible astrophysical false positives, e.g., binary stars, and to obtain a first estimate of stellar parameters. Afterward, stable and high-precision spectroscopic measurements allow us to obtain high-precision RV and line bisector (BS) time series for the stars. From this, we can estimate the orbital parameters as well as the presence and mass of the companion for systems that are confirmed as planets, and a precise set of stellar parameters. The spectroscopic observations are summarized in Table 2.

HATS-11 was observed first with the ANU 2.3 m telescope using the WiFES spectrograph and the duPont 2.5 m telescope using the echelle spectrograph. Details on the observing strategy and data reduction for the ANU 2.3 m can be found in Table 2.

### Table 1

| Instrument/Field* | Date (s) | # Images | Cadence b (s) | Filter | Precision c (mmag) |
|------------------|----------|----------|---------------|--------|-------------------|
| HATS-11          |          |          |               |        |                   |
| HS-3.1/G579      | 2010 Mar−2011 Aug | 2229 | 304 | r | 11.5 |
| HS-1.2/G579      | 2010 Mar−2011 Aug | 4298 | 301 | r | 10.8 |
| HS-3.2/G579      | 2010 Mar−2011 Aug | 2144 | 304 | r | 11.2 |
| HS-5.2/G579      | 2010 Sep−2011 Aug | 2768 | 303 | r | 10.2 |
| PEST             | 2013 Jun 15 | 138 | 131 | \( R_c \) a | 4.9 |
| Swope 1 m        | 2014 Jul 03 | 69 | 189 | i | 1.6 |
| LCOGT 1 m+SBIG   | 2014 Sep 03 | 48 | 196 | i | 3.8 |
| AAT+IRIS2        | 2014 Sep 07 | 778 | 16 | \( K_s \) | 3.7 |
| LCOGT 1 m+Sinistro | 2014 Sep 11 | 46 | 288 | i | 2.7 |
| HATS-12          |          |          |               |        |                   |
| HS-1.2/G579      | 2010 Mar−2011 Aug | 4315 | 300 | r | 5.9 |
| HS-3.2/G579      | 2010 Mar−2011 Aug | 2126 | 303 | r | 6.9 |
| HS-5.2/G579      | 2010 Sep−2011 Aug | 2781 | 303 | r | 6.1 |
| PEST             | 2013 May 24 | 193 | 130 | \( R_c \) a | 3.4 |
| MPG 2.2 m+GROND  | 2013 Jul 13 | 279 | 90 | g | 0.8 |
| MPG 2.2 m+GROND  | 2013 Jul 13 | 271 | 90 | r | 1.9 |
| MPG 2.2 m+GROND  | 2013 Jul 13 | 273 | 90 | i | 0.7 |
| DK 1.54 m+DFOSC  | 2013 Oct 03 | 98 | 145 | \( R \) | 1.9 |
| SWOPE 1 m        | 2015 May 26 | 82 | 59 | g | 2.1 |

**Notes.**

a For HATSouth data, we list the HATSouth unit, CCD, and field name from which the observations are taken. HS-1 and -2 are located at Las Campanas Observatory in Chile, HS-3 and -4 are located at the H.E.S.S. site in Namibia, and HS-5 and -6 are located at Siding Spring Observatory in Australia. Each unit has 4 ccds. Each field corresponds to one of 838 fixed pointings used to cover the full 4° celestial sphere. All data from a given HATSouth field and CCD number are reduced together, while detrending through external parameter decorrelation (EPD) is done independently for each unique unit−CCD−field combination.

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

c The rms scatter of the residuals from our best-fit transit model for each light curve at the cadence indicated in the table.

d \( R_c \) is the standard Cousins \( R \) filter.

### References

- Penev et al. (2013)
- Kovács et al. (2005)
- Bakos et al. (2010)
- Delrez et al. (2014)
in Bayliss et al. (2013) and for the duPont in Brahm et al. (2015). From these spectra, we detect no RV variations greater than $\sim 2 \text{ km s}^{-1}$ and could determine the host star’s spectral type. We verified with the new information that the transit is still consistent with a planetary companion. In light of this, we continued to observe HATS-11 with spectrographs allowing for simultaneous wavelength calibration for RV precision, namely with CORALIE at the Euler 1.2 m and FEROS at the MPG 2.2 m telescope. For both spectrographs, we made use of the reduction procedures described in Jordán et al. (2014), which gave us the RV and BS measurements of the spectrum. Similarly, HATS-12 was observed with the WiFeS and the duPont echelle spectrograph. RVs/BSs were obtained with FEROS and additionally with the HDS spectrograph at the Subaru telescope. Details on the data reduction with HDS can be found in Sato et al. (2002, 2012). The phased high-precision RV and BS measurements are shown for each system in Table 2; the data are presented in Table 6. Spectra, RVs, and BSs are used in Section 3 to reject some possible systems mimicking a planetary system.

### Table 2

| Instrument | UT Date(s)         | # Spec. | Res. $\Delta \lambda/\lambda/1000$ | S/N Range$^a$ | $\gamma_{\text{RV}}$ (km s$^{-1}$) | RV Precision$^b$ (m s$^{-1}$) |
|------------|-------------------|---------|-----------------------------------|--------------|---------------------------------|-----------------------------|
| HATS-11    |                   |         |                                   |              |                                 |                             |
| ANU 2.3 m/WiFeS | 2012 Sep 9 | 1       | 3                                 | 152          | ...                            | ...                         |
| ANU 2.3 m/WiFeS | 2012 Sep–2013 Mar | 4 | 7                                 | 19–70        | $-53.8$                        | 4000                        |
| du Pont 2.5 m/Echelle | 2013 Aug 21 | 1     | 40                                | 40           | $-58.8$                        | 500                         |
| Euler 1.2 m/Coralie | 2013 Aug–2014 Mar | 10 | 60                                | 11–17        | $-58.41$                       | 130                         |
| MPG 2.2 m/FEROS | 2013 Apr–Sep | 10 | 48                                | 16–61        | $-58.32$                       | 42                          |
| HATS-12    |                   |         |                                   |              |                                 |                             |
| MPG 2.2 m/FEROS | 2012 Aug–2013 May | 12 | 48                                | 57–107       | $-21.66$                       | 42                          |
| ANU 2.3 m/WiFeS | 2012 Sep 8 | 1       | 3                                 | 257          | ...                            | ...                         |
| Subaru 8 m/HDS+$I_2$ | 2012 Sep 19–22 | 9 | 60                                | 53–86        | ...                            | 13                          |
| Subaru 8 m/HDS | 2012 Sep 20 | 3       | 60                                | 112–118      | ...                            | ...                         |
| du Pont 2.5 m/Echelle | 2013 Aug 21 | 1 | 40                                | 58           | $-21.72$                       | 500                         |

Notes.

$^a$ S/N per resolution element near 5180 Å.

$^b$ For the CORALIE and FEROS observations of HATS-11, and for the FEROS observations of HATS-12, this is the zero-point RV from the best-fit orbit. For the WiFeS and du Pont Echelle, it is the mean of the observations. We do not provide this quantity for HDS for which only relative RVs are measured, or for the lower resolution WiFeS observations, which were only used to measure stellar atmospheric parameters.

$^c$ For high-precision RV observations included in the orbit determination, this is the scatter in the RV residuals from the best-fit orbit (which may include astrophysical jitter), for other instruments, this is either an estimate of the precision (not including jitter), or the measured standard deviation. We do not provide this quantity for low-resolution observations from the ANU 2.3 m/WiFeS or for $I_2$-free observations made with HDS, as RVs are not measured from these data.

### 2.3. Photometric Follow-up Observations

We also photometrically followed-up both candidates with larger aperture telescopes. This is necessary because the HATSouth survey telescopes have limited photometric precision, whereas the light curves obtained with these follow-up telescopes are of higher quality allowing us to better characterize the system. The distant in-time photometric follow-up observations further help us to refine the transit ephemeris. Photometric follow-up observations are summarized in Table 1. The data are given in Table 3. The light curves for HATS-11 are shown in Figure 3, while for HATS-12 they are shown in Figure 4.

We obtained photometric time series of HATS-11 with the PEST 0.3 m, Swope 1 m, and the LCOGT 1 m networks. Data...
reduction followed the established procedures described in previous HATSouth discoveries (Bayliss et al. 2013; Mohler-Fischer et al. 2013; Penev et al. 2013; Jordán et al. 2014; Zhou et al. 2014a; Brahm et al. 2015; Hartman et al. 2015; Mancini et al. 2015).

Additionally, a partial transit of HATS-11b was observed on 2014-09-07, in the $K_s$-band, using the IRIS2 infrared camera (Tinney et al. 2004) on the 3.9 m Anglo Australian Telescope, at the Siding Spring Observatory, Australia. The instrument uses a Hawaii 1-RG detector, has a field of view of 7.7′ × 7.7′,

Table 3

| Objecta | BJDb (2,400,000+) | Magc | $\sigma_{Mag}$ | Mag(orig)c | Filter | Instrument |
|---------|------------------|------|----------------|------------|--------|------------|
| HATS-11 | 55780.56087      | −0.01727 | 0.00795 | ...         | r      | HS         |
| HATS-11 | 55762.46733      | −0.01616 | 0.00787 | ...         | r      | HS         |
| HATS-11 | 55802.27850      | 0.01253 | 0.00731 | ...         | r      | HS         |
| HATS-11 | 55780.56478      | 0.01161 | 0.00824 | ...         | r      | HS         |
| HATS-11 | 55791.42313      | −0.01754 | 0.01052 | ...         | r      | HS         |
| HATS-11 | 55782.47083      | 0.02251 | 0.00825 | ...         | r      | HS         |
| HATS-11 | 55760.56823      | 0.00687 | 0.00698 | ...         | r      | HS         |
| HATS-11 | 55791.42657      | −0.01138 | 0.01137 | ...         | r      | HS         |
| HATS-11 | 55766.09292      | 0.00550 | 0.00705 | ...         | r      | HS         |

Notes.

a Either HATS-11 or HATS-12.
b Barycentric Julian Date is computed directly from the UTC time without correction for leap seconds.
c The out-of-transit level has been subtracted. For observations made with the HATSouth instruments (identified by “HS” in the “Instrument” column), these magnitudes have been corrected for trends using the EPD and TFA procedures applied prior to fitting the transit model. This procedure may lead to an artificial dilution in the transit depths. For HATS-11 the transit depth is 72% and 84% of the true depth for the G579.1 and G579.2 observations, respectively. For HATS-12 it is 100% and 78% of the true depth for the G579.4 and G580.1 observations, respectively. For observations made with follow-up instruments (anything other than “HS” in the “Instrument” column), the magnitudes have been corrected for a quadratic trend in time fit simultaneously with the transit.
d Raw magnitude values without correction for the quadratic trend in time. These are only reported for the follow-up observations.

(This table is available in its entirety in machine-readable form.)
Exposures were 15 s in duration, with a total of 931 exposures taken, lasting a total of 4.6 hr. The target remained above airmass 1.25, and drifted by less than 1 pixel throughout the observations. The telescope was defocused to achieve a PSF FWHM of $\sim 2''$, in order to minimize the effect of inter- and intra-pixel variation, and prevent saturation. The observing strategy, data reduction, and light curve analysis techniques are detailed in Zhou et al. (2014b). As opposed to optical flat fielding, for our near-infrared data we followed the procedure from Zhou et al. (2014b), where flat fielding is performed using a linear combination of two sets of dither frames taken before and after the observation. Aperture photometry is performed on each frame to extract the fluxes of the target and reference stars. The target light curve was corrected against the ensemble of reference stars, with weights to each reference star fitted to minimize the out-of-transit root mean square (rms) scatter of the target star.

All observations of HATS-11b in different filters reproduced a similar flux decrease consistent with a $R_p/R_*$ being the same in all filters and the discovery light curve. Our follow-up photometry delivered higher precision light curves though, between 1.6 and 5 mmag per point. We note that mostly partial transits were observed. Each light curve allowed us to refine and improve the uncertainties of the ephemeris, which helped us to schedule subsequent transit observations. The final ephemeris is determined through the global MCMC analysis, as explained in Section 3.3, finding them to be $T_c$(BJD) = 2456574.9657 ± 0.0013 and $P$ = 3.6191613 ± 0.0000099 days, as well as having the parameters $R_p/R_*$ = 0.1076 ± 0.0028 and $b^2$ = 0.041 ± 0.029.

HATS-12 was observed with the PEST 0.3 m, MPG 2.2 m, DK 1.54 m, and Swope 1 m telescopes. Again, their light curves were consistent with the discovery observations. For data analysis of the PEST, Swope, and MPG2.2 m observations, we repeated
our well established procedures as described in previous papers (Bayliss et al. 2013; Mohler-Fischer et al. 2013; Penev et al. 2013; Jordán et al. 2014; Zhou et al. 2014a; Brahm et al. 2015; Hartman et al. 2015; Mancini et al. 2015). For the DK 1.54 m observation on the night of 2013-10-03, we defocused the telescope. We used DFOSC, a focal reducer type camera with a $2048 \times 4096$ pixel E2V44-82 CCD. The CCD electronics was improved with a 32-bit analog–digital-converter (ADC), allowing for more levels than the usual 65,536 available in 16-bit ADCs, which are generally used for astronomical CCDs. The saturation obtained with this instrument is up to around 700,000 ADUs with a higher readout speed (400 kpix s$^{-1}$) and a higher gain of 0.24 [e$^{-}$/ADU], and the readout noise is 9.94 e$^-$. However, only half of the CCD is illuminated by the telescope and this part of the CCD is readout and generally referred to as full frame, while further windowing is generally possible. The field of view of the illuminated part is $13^{\prime\prime}7 \times 13^{\prime\prime}7$. This is sufficiently large to find adequate reference stars for our differential photometry. We choose a reference image and calculated the shift of all images with respect to the reference image. From the reference image, we extracted the position of the stars. Following Deeg & Doyle (2013), the time series photometry was generated from these observations using optimized aperture photometry that maximizes the signal-to-noise ratio (S/N) for each star. For all images in one night, we used three fixed apertures and choose these to be appropriated to the PSF in order to minimize the impact of the time-variable seeing. Depending on the telescope, for this bright object, we obtained a follow-up precision between 0.7 and 3.4 mmag per point. The subsequent refinement of the transit ephemeris was especially important for HATS-12, as the first photometric follow-up observation with the PEST 0.3 m, telescope showed the flat out-of-transit part. Despite the fact that we did not detect the transit with our initial ephemeris, this observation was still consistent with the transit having occurred after the observation, see the upper most light curve in Figure 4. This can be attributed to the precision with which we can calculate the initial ephemeris from the discovery light curve and to the propagation of the period estimation error. After we updated the ephemeris, the following photometric observation with GROND finally revealed the transit. Again, using the

Figure 4. Similar to Figure 3; here we show the follow-up light curves for HATS-12. The PEST 0.3 m, observation shows a flat out-of-transit part. However, the observation helped to refine the ephemeris and the subsequent GROND observation detected the transit, see the text.
## Stellar Parameters for HATS-11 and HATS-12

| Parameter                     | HATS-11      | HATS-12      | Source          |
|-------------------------------|--------------|--------------|-----------------|
| **Astrometric properties and cross-identifications** |              |              |                 |
| 2MASS-SD                      | 2MASS        | 2MASS        |                 |
| 19173618                      | 19164857     |              |                 |
| !!!                           | −2223236     | −1921212     | 2MASS           |
| GSC-Id                        | GSC 6308     | GSC 6304     |                 |
| −00430                        | −00396       |              |                 |
| R.A. (J2000)                  | 19^h17^m36^s24 | 19^h16^m48^s72 | 2MASS |
| Dec. (J2000)                  | −22°23′23″7    | −19°21′21″2    | 2MASS           |
| µR.A. (mas yr⁻¹)              | 4.5 ± 1.9    | 6.2 ± 4.0    | UCAC4           |
| µDec. (mas yr⁻¹)              | −21.5 ± 1.9  | 5.2 ± 2.7    | UCAC4           |
| **Galactic space velocity components, LSR reference frame** |              |              |                 |
| u (km s⁻¹)                    | 65.274       | 25.812       | FEROS+UCAC4     |
| v (km s⁻¹)                    | 88.956       | 37.784       | FEROS+UCAC4     |
| w (km s⁻¹)                    | 40.364       | −4.115       | FEROS+UCAC4     |
| **Spectroscopic properties**  |              |              |                 |
| \( T_{\text{eff}} \) (K)     | 6060 ± 150   | 6408 ± 75    | ZASPE²          |
| [Fe/H]                        | −0.390 ± 0.060 | −0.100 ± 0.040 | ZASPE          |
| \( v \sin i \) (km s⁻¹)      | 3.8 ± 1.0    | 6.57 ± 0.50  | ZASPE           |
| \( \gamma_{\text{RV}} \) (km s⁻¹) | −58.324 ± 0.012 | −21.661 ± 0.012 | FEROS⁴         |
| **Photometric properties**    |              |              |                 |
| \( B \) (mag)                 | 14.657 ± 0.019 | 13.258 ± 0.043 | APASS¹         |
| \( V \) (mag)                 | 14.018 ± 0.081 | 12.736 ± 0.021 | APASS¹         |
| \( g \) (mag)                 | 14.268 ± 0.012 | 12.972 ± 0.005 | APASS¹         |
| \( r \) (mag)                 | 13.865 ± 0.039 | 12.654 ± 0.015 | APASS¹         |
| \( i \) (mag)                 | 13.506 ± 0.234 | 12.595 ± 0.021 | APASS¹         |
| \( J \) (mag)                 | 12.647 ± 0.023 | 11.725 ± 0.023 | 2MASS          |
| \( H \) (mag)                 | 12.315 ± 0.025 | 11.507 ± 0.024 | 2MASS          |
| \( K_s \) (mag)               | 12.243 ± 0.025 | 11.391 ± 0.023 | 2MASS          |
| **Derived properties**        |              |              |                 |
| \( M_r \) (M_\odot)           | 1.000 ± 0.060 | 1.489 ± 0.071 | YY+\( \rho_\star \)+ZASPE² |
| \( R_\star \) (R_\odot)       | 1.444 ± 0.057 | 2.21 ± 0.21  | YY+\( \rho_\star \)+ZASPE² |
| \( \log g_\star \) (cgs)      | 4.118 ± 0.026 | 3.923 ± 0.065 | YY+\( \rho_\star \)+ZASPE² |
| \( \rho_\star \) (g cm⁻³)     | 0.471^{+0.037}_{-0.052} | 0.196^{+0.057}_{-0.044} | YY+\( \rho_\star \)+ZASPE² |
| \( L_\star \) (L_\odot)       | 2.53 ± 0.39  | 7.3 ± 1.5    | YY+\( \rho_\star \)+ZASPE² |
| \( M_V \) (mag)               | 3.81 ± 0.18  | 2.58 ± 0.22  | YY+\( \rho_\star \)+ZASPE² |
| \( M_K \) (mag,ESO)           | 2.44 ± 0.10  | 1.47 ± 0.21  | YY+\( \rho_\star \)+ZASPE² |
| \( \text{Age} \) (Gyr)        | 7.7^{+2.2}_{-1.6} | 2.36 ± 0.31  | YY+\( \rho_\star \)+ZASPE² |
| \( \Delta V \) (mag)          | 0.42 ± 0.15  | 0.228 ± 0.068 | YY+\( \rho_\star \)+ZASPE² |
| **Distance (pc)**             | 906 ± 41     | 981 ± 94     | YY+\( \rho_\star \)+ZASPE² |

Notes.

1. ZASPE—Zonal Atmospheric Stellar Parameter Estimator routine for the analysis of high-resolution spectra (Brahm et al. 2016, in preparation), applied to the FEROS spectra of HATS-11 and HATS-12. These parameters rely primarily on ZASPE, but have a small dependence also on the iterative analysis incorporating the isochrone search and global modeling of the data.

2. The error on \( \gamma_{\text{RV}} \) is determined from the orbital fit to the FEROS RV measurements and does not include the systematic uncertainty in transforming the velocities from FEROS to the IAU standard system.

3. From APASS DR9 (Henden & Munari 2014).

4. YY+\( \rho_\star \)+ZASPE = Based on the YY isochrones Yi et al. (2001), \( \rho_\star \) as a luminosity indicator, and the ZASPE results.

3. ANALYSIS

### 3.1. Properties of the Parent Star

In order to obtain the physical parameters of the newly discovered planets, we have to characterize their stellar hosts. We determined precise atmospheric parameters for HATS-11 and HATS-12 from the median combined FEROS spectra. The SNR of both combined spectra was ~50 per resolution element. We applied the algorithm ZASPE (Brahm et al. 2016) to both spectra, which determines \( T_{\text{eff}}, \log \, g, [\text{Fe/H}], \) and \( v \sin i \) via least-squares minimization against a grid of synthetic spectra from Husser et al. (2013) in the most sensitive regions of the wavelength coverage to changes in the atmospheric parameters. ZASPE obtains reliable errors and correlations between the

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**Notes:**

- ZASPE—Zonal Atmospheric Stellar Parameter Estimator routine for the analysis of high-resolution spectra (Brahm et al. 2016, in preparation), applied to the FEROS spectra of HATS-11 and HATS-12. These parameters rely primarily on ZASPE, but have a small dependence also on the iterative analysis incorporating the isochrone search and global modeling of the data.

- The error on \( \gamma_{\text{RV}} \) is determined from the orbital fit to the FEROS RV measurements and does not include the systematic uncertainty in transforming the velocities from FEROS to the IAU standard system.

- From APASS DR9 (Henden & Munari 2014).

- YY+\( \rho_\star \)+ZASPE = Based on the YY isochrones Yi et al. (2001), \( \rho_\star \) as a luminosity indicator, and the ZASPE results.
parameters that takes into account the systematic mismatch between the data and the optimal synthetic spectra.

The $T_{\text{eff}}$ and [Fe/H] values from ZASPE were combined with the stellar density ($\rho_*$) which was obtained through our joint light curve and RV curve analysis to determine a first estimation of the stellar physical parameters (Sozzetti et al. 2007). In particular, we search for the parameters of the Yonsei-Yale (Y2; Yi et al. 2001) isochrones (stellar mass, radius, and age) that produce the best match with our estimated $T_{\text{eff}}$, [Fe/H], and $\rho_*$ values. Then we compute a new value for log $g$, which is held fixed in a second run of ZASPE and a subsequent comparison with the theoretical isochrones is made. The final adopted parameters for HATS-11 and HATS-12 are given in Table 4. Figure 5 shows the locations of each star on a $T_{\text{eff}}$–$\rho_*$ diagram. We found after performing the analysis that both stars are slightly evolved metal-poor stars. HATS-11 has a mass of $1.0 \pm 0.06 M_\odot$, a radius of $1.444 \pm 0.057 R_\odot$, and an age of 7.7 $\pm$ 2 Gyr, while the parameters for HATS-12 are $1.489 \pm 0.071 M_\odot$, 2.21 $\pm$ 0.21 $R_\odot$, and an age of 2.36 $\pm$ 0.3 Gyr. Distances are determined by comparing the measured broadband photometry listed in Table 4 to the predicted magnitudes in each filter from the isochrones. We assume a $R_V = 3.1$ extinction law from Cardelli et al. (1989) to determine the extinction.

### 3.2. Excluding Blend Scenarios

In order to exclude blend scenarios, we carried out an analysis following Hartman et al. (2012). We attempt to model the available photometric data (including light curves and catalog broadband photometric measurements) for each object as a blend between an eclipsing binary star system and a third star along the line of sight. The physical properties of the stars are constrained using the Padova isochrones (Girardi et al. 2000), while we also require that the brightest of the three stars in the blend have atmospheric parameters consistent with those measured with ZASPE.

For HATS-11, we find that the best-fit blend model provides a poorer fit to the data than the best-fit planet+star model, and can be rejected with 3$\sigma$ confidence. Based on simulating composite spectra for the blend models that we tested, we also find that any blended eclipsing binary system that can plausibly fit the photometric data (i.e., cannot be rejected with more than 5$\sigma$ confidence) would show BS variations ranging from 400 m s$^{-1}$ for the model that provides the most marginal fit (i.e., at the 5$\sigma$ rejection limit), to more than 1 km s$^{-1}$ for the best-fitting blend models, as well as having RV variations with $K > 200$ m s$^{-1}$. As the measured BS variation is 80 m s$^{-1}$ for FEROS and 140 m s$^{-1}$ for Coralie, and the RV semi-amplitude is 112 $\pm$ 15 m s$^{-1}$, we conclude that HATS-11 is not a blended stellar eclipsing binary system, and that the observations favor a transiting planet system interpretation. Similarly, for HATS-12, we find that the best-fit blend model provides a poorer fit to the data than the best-fit planet+star model, and in this case can be rejected with 2$\sigma$ confidence. Those blended eclipsing binary systems that cannot be rejected with more than 5$\sigma$ confidence based solely on the photometry would have easily been detected as composite systems based on the FEROS and HDS spectroscopy, and would have BS variations exceeding 1 km s$^{-1}$. For comparison, the BS rms scatter is 34 m s$^{-1}$ and 15 m s$^{-1}$ for the FEROS and HDS observations of HATS-12, respectively. We conclude that HATS-12 is also not a blended stellar eclipsing binary system, and is instead a transiting planet system. However, both system could still be diluted transiting planet systems, which cannot be recognized by spectroscopic observations and only high angular resolution imaging can solve. If a blended stellar companion is present, diluting the light of the transiting system, then the true companion radius could be up to 60% larger than inferred.

### 3.3. Global Modeling of the Data

We modeled the HATSouth photometry, the follow-up photometry, and the high-precision RV measurements following Pál et al. (2008), Bakos et al. (2010) and Hartman et al. (2012). We fit Mandel & Agol (2002) transit models to the light curves, allowing for a dilution of the HATSouth transit depth as a result of blending from neighboring stars and over-correction by the trend-filtering method. For the follow-up light curves, we include a quadratic trend in time in our model for each event to correct for remaining systematic errors in the photometry. We fit Keplerian orbits to the RV curves allowing the zero-point for each instrument to vary independently in the fit, and allowing for RV jitter, which we also vary as a free

**Figure 5.** Model isochrones from Yi et al. (2001) for the measured metallicities of HATS-11 (left) and HATS-12 (right). For HATS-11, we show models for ages of 0.2 Gyr and 1.0–14.0 Gyr in 1.0 Gyr increments (ages increasing from left to right), while for HATS-12, we show models for ages of 0.2 Gyr, for 0.5–2.0 Gyr in 0.25 Gyr increments, and for 2.0–5.0 Gyr in 0.5 Gyr increments. The adopted values of $T_{\text{eff}}$, and $\rho_*$ are shown together with their 1$\sigma$ and 2$\sigma$ confidence ellipsoids. The initial values of $T_{\text{eff}}$, and $\rho_*$ from the first ZASPE and light curve analyses are represented with a triangle.
Table 5
Orbital and Planetary Parameters for HATS-11b and HATS-12b

| Parameter                        | HATS-11b Value       | HATS-12b Value       |
|----------------------------------|----------------------|----------------------|
| **Light curve parameters**       |                      |                      |
| \(P\) (days)                     | 3.6191613 ± 0.0000099| 3.142833 ± 0.00011   |
| \(T_0\) (BID)\(^a\)             | 2456574.9657 ± 0.0013| 2456798.9556 ± 0.0012|
| \(T_{14}\) (days)\(^a\)         | 0.1819 ± 0.0039      | 0.1899 ± 0.0031      |
| \(T_{12} = T_{14}\) (days)\(^a\) | 0.0184 ± 0.0012      | 0.0167 ± 0.0033      |
| \(a/R_p\)                        | 6.88\(^{+0.18}_{-0.37}\) | 4.67 ± 0.38          |
| \(\zeta/R_p\)\(^b\)             | 12.23 ± 0.26         | 11.54 ± 0.12         |
| \(R_p/R_\star\)                 | 0.1076 ± 0.0028      | 0.0630 ± 0.0022      |
| \(b^2\)                          | 0.041\(^{+0.060}_{-0.059}\) | 0.347\(^{+0.099}_{-0.102}\) |
| \(b \equiv a \cos i/R_\star\)   | 0.203\(^{+0.115}_{-0.114}\) | 0.589\(^{+0.079}_{-0.126}\) |
| \(i\) (deg)                      | 88.31 ± 0.86         | 82.7 ± 1.9           |
| **Limb-darkening coefficients**  |                      |                      |
| \(c_1\), \(g\) (linear term)    | ...                  | 0.4153               |
| \(c_2\), \(g\) (quadratic term) | ...                  | 0.3276               |
| \(c_3\), \(r\)                   | 0.2778               | 0.2509               |
| \(c_4\), \(r\)                   | 0.3619               | 0.3789               |
| \(c_5\), \(i\)                   | 0.2115               | 0.1762               |
| \(c_6\), \(i\)                   | 0.3464               | 0.3706               |
| \(c_7\), \(R\)                   | 0.2590               | 0.2295               |
| \(c_8\), \(R\)                   | 0.3590               | 0.3783               |
| \(c_9\), \(K\)                   | −0.0081              | ...                  |
| \(c_{10}\), \(K\)                | 0.3305               | ...                  |
| **RV parameters**                |                      |                      |
| \(K\) (m s\(^{-1}\))            | 112 ± 15             | 250.6 ± 9.4          |
| \(e\)\(^d\)                      | <0.340               | <0.085               |
| RV jitter FEROS (m s\(^{-1}\))   | <22.1                | 31 ± 16              |
| RV jitter Coralie (m s\(^{-1}\)) | <26.3                | ...                  |
| RV jitter HDS (m s\(^{-1}\))     | ...                  | <20.0                |
| **Planetary parameters**         |                      |                      |
| \(M_p\) (\(M_\odot\))           | 0.85 ± 0.12          | 2.38 ± 0.11          |
| \(R_p\) (\(R_\odot\))           | 1.510 ± 0.078        | 1.35 ± 0.17          |
| \(C(M_p, R_p)\)\(^f\)           | 0.15                 | 0.57                 |
| \(\rho_p\) (g cm\(^{-3}\))      | 0.299\(^{+0.071}_{-0.060}\) | 1.19\(^{+0.31}_{-0.32}\) |
| \(\log g_p\) (cgs)              | 2.959 ± 0.071        | 3.506 ± 0.095        |
| \(a\) (AU)                       | 0.04614 ± 0.000093   | 0.04795 ± 0.00077    |
| \(T_0\) (K)                      | 1637 ± 48            | 2097 ± 89            |
| \(\Theta\)\(^g\)                | 0.0514 ± 0.0076      | 0.112\(^{+0.018}_{-0.012}\) |
| \(\log_{10}(F)\) (cgs)\(^h\)    | 9.211 ± 0.050        | 9.640 ± 0.074        |

**Notes.** For both objects, we list the parameters assuming circular orbits. Based on Bayesian evidence, we find that such an orbit is preferred for both systems.

\(^a\) Times are in Barycentric Julian Date, calculated directly from UTC without correction for leap seconds. \(T_0\): reference epoch of mid-transit that minimizes the correlation with the orbital period. \(T_{12}\): total transit duration, time between first to last contact; \(T_{12} = T_{14}\): ingress/egress time, time between first and second, or third and fourth contact.

\(^b\) Reciprocal of the half duration of the transit used as a jump parameter in our MCMC analysis in place of \(a/R_\star\).

It is related to \(a/R_\star\) by the expression \(\zeta/R_\star = a/R_\star(2\pi(1 + e \sin \omega))/(P \sqrt{1 - e^2})\) (Bakos et al. 2010). \(\zeta/R_\star\) is used in the RV jitter equation.

\(^c\) Values for a quadratic law, adopted from the tabulations by Claret (2004) according to the spectroscopic (ZASPE) parameters listed in Table 4.

\(^d\) For fixed circular orbit models, we list the 95% confidence upper limit on the eccentricity determined when \(\sqrt{e} \cos \omega\) and \(\sqrt{e} \sin \omega\) are allowed to vary in the fit.

\(^e\) Error term, either astrophysical or instrumental in origin, added in quadrature to the formal RV errors for the listed instrument. We give the 95% confidence upper limit when the jitter is consistent with 0 m s\(^{-1}\).

\(^f\) Correlation coefficient between the planetary mass \(M_p\) and radius \(R_p\) estimated from the posterior parameter distribution.

\(^g\) The Safronov number is given by \(\Theta = 1/2(V_{esc}/V_{orb})^2 = (a/R_p)(M_p/M_\star)\) (see Hansen & Barman 2007).

\(^h\) Incoming flux per unit surface area, averaged over the orbit.
parameter for each instrument. This jitter may be astrophysical or instrumental in nature, and simply represents excess scatter in the RV observations beyond what is expected based on formal uncertainties.

We used a Differential Evolution Markov Chain Monte Carlo procedure to explore the fitness landscape and to determine the posterior distribution of the parameters (DEMCMC; ter Braak 2006). Note that we tried fitting both fixed circular orbits and free-eccentricity models to the data, and for both systems find that the data are consistent with a circular orbit. For both systems, the fixed circular orbit model has higher Bayesian evidence so we adopt the parameters obtained assuming no eccentricity for both objects. Furthermore, we see no structure or drift within our uncertainties that could hint to any extra component in the system. We also note that, for HATS-11, the scatter in the CORALIE and FEROS RV residuals is consistent with the uncertainties, so our modeling finds jitter values of 0 for both instruments. Similarly, we find that a jitter value of 0 is preferred for the HDS observations of HATS-12. For these instruments, we list the 95% upper limit on the jitter in Table 5. The resulting parameters for each system are listed in Table 5. Figure 6 shows the posterior probability distributions for the parameters \( T_c \), semi-amplitude \( K \), \( R_p/R_* \), \( \beta^2 \), and \( \zeta/R_* \) as computed by our DEMCMC and marginalized over the other parameters. All parameters are mostly mutually uncorrelated. Only for HATS-12b we see a slight correlation between the impact parameter \( b \) and \( R_p/R_* \) through the effect of limb darkening. For HATS-11b, this correlation is not as prominent as for HATS-12b due to its impact parameter close to zero. HATS-11b has a mass slightly smaller than Jupiter (0.85 ± 0.12 \( M_J \)) and a large radius of 1.51 ± 0.078 \( R_J \). It is a moderately irradiated hot Jupiter with an equilibrium temperature of 1637 ± 48 K. HATS-12b is a rather massive hot Jupiter with 2.38 ± 0.11 \( M_J \), 1.35 ± 0.17 \( R_J \), and a relatively high equilibrium temperature of 2097 ± 89 K.

**4. DISCUSSION**

In this paper, we have presented HATS-11b and HATS-12b, two inflated gas giants orbiting subsolar metallicity stars with [Fe/H] of \(-0.390 ± 0.060\) and \(-0.100 ± 0.040\), respectively. Globally fitting all observations, we estimated precise system parameters as shown in Tables 4 and 5.

HATS-11b and HATS-12b are two regular hot Jupiters that present inflated radii as compared to predictions of standard theoretical models of planetary structure. However, a distinction of these transiting systems is that both of them have low-metallicity stellar hosts that are evolved.

Figure 7 shows a histogram of metallicity for known transiting hot-Jupiter planet hosts. The systems’ parameters were taken from the Transiting Extrasolar Planet Catalogue (TEPCat). We limited the sample to systems comparable to our discovered planets in this work by restricting it to TEPs, satisfying \( M_p \geq 0.47M_J \), \( 0.015 \leq a \leq 0.5 \) au, and around stars with \( 5300 \, K \leq T_{\text{eff}} \leq 7200 \, K \) (stellar spectral type G to F). The choice of 0.47 \( M_J \) for the minimum mass is made based on the findings of Weiss et al. (2013) who found a break in the radius–mass relation at that mass. We also restrict the sample to have uncertainties in [Fe/H] ≤ 0.15 dex. As is now well established, giant planets are found less frequently around metal-poor stars. We note that HATS-11 is among the most metal-poor stars detected to harbor a transiting giant planet. The two planets in the lowest metallicity bin are WASP-58 ([Fe/H] = −0.45 dex Hébrard et al. 2013) and WASP-87 ([Fe/H] = −0.41 dex Anderson et al. 2014). Thus, HATS-11 has the value of populating a sparse region of parameter space necessary to understand and validate planet formation theories. In particular, planets as massive as HATS-11b around stars with such a low metallicity can help to empirically constrain limits on the metallicity of the nebulae in the context of core-accretion.

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10 Available at http://www.astro.keele.ac.uk/jkt/tepcat/.
theory, which can give insights to the boundaries of the formation process (Matsuo et al. 2007).

In Figure 8, we show stellar surface gravity as function of stellar radius for the same sample as in Figure 7. HATS-11 is a slightly evolved metal-poor star. Only two other systems resemble similar stellar parameters ($R_s \sim 1.4$–1.5 $R_\odot$ and $\log g \sim 4.1$), namely HATS-9 (Brahm et al. 2015) and WASP-48 (Enoch et al. 2011), but none of them are metal-poor. Amongst the most evolved hot-Jupiter hosts only two have a low metal content, namely HATS-12 and Kepler-435 ($R_s = 3.21 R_\odot$, $M_s = 1.538 M_\odot$, Almenara et al. 2015). No subsolar metallicity stars with similar stellar radius and surface gravity to HATS-12

| BJD(2,456,000+) | RV (m s$^{-1}$) | $\sigma_{RV}$ (m s$^{-1}$) | BS (m s$^{-1}$) | $\sigma_{BS}$ (m s$^{-1}$) | Phase | Instrument |
|-----------------|-----------------|-----------------------------|-----------------|-----------------------------|-------|------------|
| 400.76268       | 105.00          | 31.00                       | 88.0            | 62.0                        | 0.867 | FEROS      |
| 411.71442       | –23.00          | 47.00                       | 21.0            | 94.0                        | 0.893 | FEROS      |
| 424.85662       | –17.00          | 31.00                       | –56.0           | 62.0                        | 0.524 | FEROS      |
| 427.74603       | –135.00         | 80.00                       | 203.0           | 160.0                       | 0.322 | FEROS      |
| 488.81286       | –55.00          | 31.00                       | –12.0           | 62.0                        | 0.195 | FEROS      |
| 490.79732       | 136.00          | 29.00                       | 12.0            | 58.0                        | 0.744 | FEROS      |
| 492.73173       | –100.00         | 28.00                       | –51.0           | 56.0                        | 0.278 | FEROS      |
| 524.50152       | –103.59         | 80.00                       | 213.0           | 160.0                       | 0.057 | Coralie    |
| 524.56679       | 34.41           | 69.00                       | 106.0           | 138.0                       | 0.075 | Coralie    |
| 525.49132       | –374.59         | 116.00                      | –76.0           | 232.0                       | 0.330 | Coralie    |
| 544.52715       | 61.00           | 33.00                       | 75.0            | 66.0                        | 0.590 | FEROS      |
| 548.59572       | 139.00          | 25.00                       | –27.0           | 50.0                        | 0.714 | FEROS      |
| 552.55423       | 105.00          | 30.00                       | –21.0           | 60.0                        | 0.808 | FEROS      |
| 727.88749       | –126.59         | 75.00                       | –171.0          | 150.0                       | 0.254 | Coralie    |
| 728.85790       | 78.41           | 89.00                       | –30.0           | 178.0                       | 0.522 | Coralie    |
| 729.90376       | 114.41          | 88.00                       | –157.0          | 176.0                       | 0.811 | Coralie    |
| 730.90303       | –105.59         | 144.00                      | 30.0            | 288.0                       | 0.087 | Coralie    |
| 731.89440       | 40.41           | 141.00                      | 51.0            | 282.0                       | 0.361 | Coralie    |
| 732.86378       | 246.41          | 143.00                      | 247.0           | 286.0                       | 0.629 | Coralie    |

Notes. Note that for the HDS iodine-free template exposures we do not measure the RV but do measure the BS. Such template exposures can be distinguished by the missing RV value. The HDS observation of HATS-12 without a BS measurement has too low S/N in the I$_2$-free blue spectral region to pass our quality threshold for calculating accurate BS values.

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

b Internal errors excluding the component of astrophysical jitter considered in Section 3.3.

c For FEROS and Coralie, we take the BS uncertainty to be twice the RV uncertainty. For HDS, the BS uncertainty is taken to be the standard error on the mean of the BS values calculated for each of the Échelle orders.
have now been observed, and data is expected to be released on 2016 April 30. The high-precision K2 data will allow us to improve their transit parameters, especially important for HATS-12, as it shows the third shallowest ground-based transit discovery to date. Furthermore, we will have the possibility to search intensively for additional companions through the discovery of additional transits of longer period planets, see, e.g., Rabus et al. (2009a), or transit timing variations (Rabus et al. 2009b), such as were measured in the hot Jupiter WASP-47b (Becker et al. 2015). The discovery of HATS-11b and HATS-12b thus provides a strong motivation for a combination of both ground-based detection and subsequent space-based follow-up characterization that can be fruitful and efficient.

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