HATS-59b,c: A Transiting Hot Jupiter and a Cold Massive Giant Planet around a Sunlike Star

Sarkis, P.; Henning, Th.; Hartman, J. D.; Bakos, G. A.; Brahm, R.; Jordan, A.; Bayliss, D.; Mancini, L.; Espinoza, N.; Rabus, M.

Published in:
Astrophysical Journal

Link to article, DOI:
10.3847/1538-3881/aade54

Publication date:
2018

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Sarkis, P., Henning, T., Hartman, J. D., Bakos, G. A., Brahm, R., Jordan, A., ... Sari, P. (2018). HATS-59b,c: A Transiting Hot Jupiter and a Cold Massive Giant Planet around a Sunlike Star. Astrophysical Journal, 156(5), [216]. https://doi.org/10.3847/1538-3881/aade54

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.
HATS-59b,c: A Transiting Hot Jupiter and a Cold Massive Giant Planet around a Sun-like Star*

P. Sarkis1,2, Th. Henning1, D. Hartman2, G. A. Bakos2,21,22, R. Brah1,3,4, A. Jordán1,3,4, D. Bayliss5, L. Mancini1,6,7, N. Espinoza1,3,4, M. Rabus1,3, Z. Csubry2, W. Bhatti1, K. Peney8, G. Zhou1, J. Bento10, T. G. Tan11, P. Arrigada12, R. P. Butler13, J. D. Crane13, S. Shectman13, C. G. Tinney14,15, D. J. Wright14,15, B. Addison16, S. Durkan17, V. Suc18, L. A. Buchhave18, M. de Val-Borro19, J. Lázár20, I. Papp20, and P. Sár10

1 Max Planck Institute for Astronomy, Heidelberg, Germany; sarkis@mpia.de
2 Department of Astrophysical Sciences, Princeton University, NJ 08544, USA
3 Institute for Astrophysics, Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, 7820436 Macul, Santiago, Chile
4 Millennium Institute of Astrophysics, Av. Vicuña Mackenna 4860, 7820436 Macul, Santiago, Chile
5 Department of Physics, University of Warwick, Coventry CV4 7AL, UK
6 Department of Physics, University of Rome Tor Vergata, Via della Ricerca Scientifica 1, I-00133 Rome, Italy
7 INAF–Astrophysical Observatory of Turin, via Osservatorio 20, I-10025 Pino Torinese, Italy
8 Physics Department, University of Texas at Dallas, 800 W Campbell Rd. MS WT15, Richardson, TX 75080, USA
9 Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
10 Research School of Astronomy and Astrophysics, Australian National University, Canberra, ACT 2611, Australia
11 Physics Department, University of Texas at Dallas, 800 W Campbell Rd. MS WT15, Richardson, TX 75080, USA
12 Department of Terrestrial Magnetism, Carnegie Institution for Science, Washington, DC 20015, USA
13 The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA
14 Australian Centre for Astrobiology, School of Physics, University of New South Wales, NSW 2052, Australia
15 Exoplanetary Science at ANU, School of Physics, University of New South Wales, NSW 2052, Australia
16 Mississippi State University, Department of Physics & Astronomy, Hilburn Hall, Starkville, MS 39762, USA
17 Astrophysics Research Centre, Queens University, Belfast, Belfast, Northern Ireland, UK
18 DTU Space, National Space Institute, Technical University of Denmark, Elektrovej 328, DK-2800 Kgs. Lyngby, Denmark
19 Astrochemistry Laboratory, Goddard Space Flight Center, NASA, 8800 Greenbelt Rd., Greenbelt, MD 20771, USA
20 Hungarian Astronomical Association, 1451 Budapest, Hungary

Received 2018 May 13; revised 2018 August 24; accepted 2018 August 29; published 2018 October 18

Abstract

We report the first discovery of a multi-planetary system by the HATSouth network, HATS-59b,c, a planetary system with an inner transiting hot Jupiter and an outer cold massive giant planet, which was detected via radial velocity. The inner transiting planet, HATS-59b, is on an eccentric orbit with $e = 0.129 \pm 0.049$, orbiting a $V = 13.951 \pm 0.030$ mag solar-like star ($M_*=1.038 \pm 0.039\,M_\odot$ and $R_*=1.036 \pm 0.067\,R_\odot$) with a period of 5.416081 $\pm 0.000016$ days. The outer companion, HATS-59c is on a circular orbit with $m \sin i = 12.70 \pm 0.87\,M_J$ and a period of 1422 $\pm 14$ days. The inner planet has a mass of $0.806 \pm 0.069\,M_J$ and a radius of $1.126 \pm 0.077\,R_J$, yielding a density of $0.70 \pm 0.16\,g\,cm^{-3}$. Unlike most planetary systems that include only a single hot Jupiter, HATS-59b,c includes, in addition to the transiting hot Jupiter, a massive outer companion. The architecture of this system is valuable for understanding planet migration.

1. Introduction

During the past decade, the number of exoplanets has increased steadily and by now more than 3500 exoplanets have been statistically validated. Exoplanets are very common and have a wide variety of properties (for a review, see Winn & Fabrycky 2015), which offer a unique opportunity to constrain their formation and evolution (Mordasini et al. 2016; Jin & Mordasini 2018). Hot Jupiters, i.e., gas giant planets on short orbital periods, still pose many challenges for planet formation models. It is believed that such planets formed beyond the ice-line, several au from the central star, and migrated inwards through interactions with the disk (e.g., Lin et al. 1996). However, disk migration predicts circular and aligned orbits (e.g., Goldreich & Tremaine 1980; Artyomowicz 1993) and cannot explain the existence of several hot Jupiters that have been found on retrograde or misaligned orbits (for a review see Winn & Fabrycky 2015). Alternative scenarios have been thus proposed, which involve interactions with a third distant body or planet–planet scattering that can result in eccentric and misaligned orbits (Kozai 1962; Lidov 1962; Nagasawa et al. 2008; Li et al. 2014; Petrovich 2015).

One approach to put constraints on the different migration mechanisms is to measure the spin–orbit alignment via the
Rossiter-McLaughlin effect (e.g., Queloz et al. 2000; Zhou et al. 2015). Another approach is to search for planetary or stellar companions at large separations, which could have influenced the dynamical evolution of the inner planet. Knutson et al. (2014) performed a long-term radial velocity monitoring of 51 systems known to host a hot Jupiter, with the goal to detect further planetary companions. They estimated an occurrence rate of 51% ± 10% for companions with masses between 1 and 13MJ and orbital semimajor axes between 1 and 20 au. Ngo et al. (2015) presented the results on searching for stellar companions around 50 out of the 51 selected systems from Knutson et al. (2014) study. They corrected for survey incompleteness and reported a stellar companion fraction of 48% ± 9%. Combining the results of both studies, Ngo et al. (2015) estimated that 72% ± 16% of hot Jupiters are part of multi-planet and/or multi-star systems.

In this work, we report the discovery of HATS-59b,c, the first multi-planet system detected by the HATSouth survey (Bakos et al. 2013). The star hosts an inner hot Jupiter detected via its transits and an outer cold massive giant planet detected via the radial velocity variations of the host star. The possibility of additional outer planetary companions to transiting hot Jupiters has been proposed by, e.g., Rabus et al. (2009) and in fact, there have been only a few transiting planets with an outer planetary companion for which a full orbit was detected via radial velocity, such as HAT-P-13b,c (Bakos et al. 2009), HAT-P-17b,c (Howard et al. 2012), Kepler-424b,c (Endl et al. 2014), WASP-41b,c (Neveu-VanMalle et al. 2016), WASP-47b,c (Hellier et al. 2012; Becker et al. 2015; Neveu-VanMalle et al. 2016), and WASP-53b,c (Triaud et al. 2017). Among all the systems with a transiting hot Jupiter known to have outer companions, HAT-P-13 c and WASP-53b,c are the only massive planetary companions with a minimum mass greater than HATS-59 c. The few detections of companions around transiting planets is due, to some extent, by the lack of radial velocity follow-up observations. Hot Jupiters in multi-planet systems provide a unique opportunity to place observational constraints on migration models and also could be used to probe the tidal love number of the hot Jupiter (Buhler et al. 2016; Hardy et al. 2017), which in turn constrains the planetary interior structure (Batygin et al. 2009). Therefore, monitoring these systems is very interesting for planet formation and interior structure models.

The paper is structured as follows: In Section 2, we show the planetary signal detected by the HATSouth network and present the photometric and spectroscopic follow-up observations that allowed us to characterize the system. In Section 3, we derive the stellar parameters and jointly model the data to derive the planetary parameters. Our results are finally summarized in Section 4.

2. Observations

2.1. Photometry

2.1.1. Photometric Detection

The HATS-59 system was identified by the HATSouth instruments as potentially hosting a transiting planet. The star (Table 3) was observed between UT 2010 January 19 and UT 2010 August 10 using the HS-1, HS-3, and HS-5 units at the Las Campanas Observatory (LCO) in Chile, the H.E.S.S. site in Namibia, and the Siding Springs Observatory (SSO) in Australia, respectively. A total of 3113, 4690 and 658 of useful images were obtained with the HS-1, HS-3, and HS-5 telescopes, respectively, using the Sloan r filter with an exposure time of 240 s.

Similar to previous HATSouth discoveries, all the photometry data were reduced to trend-filtered light curves using the aperture photometry pipeline described by Penev et al. (2013). Systematic variations were removed using the External Parameter Decorrelation (EPD; Bakos et al. 2010) and the Trend Filtering Algorithm (TFA; Kovács et al. 2005). Then a transit search was performed using the Box Least Squares (BLS; Kovács et al. 2002) fitting algorithm and a period of 5.4161 was detected (Figure 1; the data is provided in Table 1). The rms scatter after subtracting the best-fit model transit is 0.012 mag. The star was then flagged as a planet-host candidate

| BJD  |
|------|
| Mag^a | Mag (orig)^b |
| Filter | Instrument |
| (2,400,000+) | | |
| 55372.26299 | −0.01448 | 0.00725 | ... | r | HS/G563.1 |
| 55274.77568 | 0.01224 | 0.00650 | ... | r | HS/G563.1 |
| 55296.44071 | 0.01384 | 0.00668 | ... | r | HS/G563.1 |
| 55274.77891 | −0.01225 | 0.00628 | ... | r | HS/G563.1 |
| 55296.44428 | −0.00169 | 0.00659 | ... | r | HS/G563.1 |
| 55274.78240 | −0.01307 | 0.00627 | ... | r | HS/G563.1 |
| 55296.44754 | −0.00042 | 0.00652 | ... | r | HS/G563.1 |
| 55274.78651 | 0.00435 | 0.00643 | ... | r | HS/G563.1 |
| 55296.45080 | −0.00521 | 0.00660 | ... | r | HS/G563.1 |
| 55372.27744 | 0.00356 | 0.00771 | ... | r | HS/G563.1 |

Notes. The data are also available on the HATSouth website at http://www.hatsouth.org.

^ a The out-of-transit level has been subtracted. For the HATSouth light curve (rows with “HS” in the Instrument column), these magnitudes have been detrended using the EPD and TFA procedures prior to fitting a transit model to the light curve. The magnitudes of the follow-up light curves (rows with an Instrument other than “HS”) have been detrended with the EPD procedure, which was carried out simultaneously with the transit fit.

^ b Raw magnitude values for the follow-up light curve without applying the EPD procedure.

Figure 1. The discovery light curve of HATS-59 phase-folded with a period of \( P = 5.4160810 \) days (see Section 3). The lower panel shows the transit where the filled black points show the light curve binned in phase with a bin size of 0.002. The solid lines in both panels show the best-fit transit model.
and approved for further follow-up photometric and spectroscopic observations.

2.1.2. Photometric Follow Up

In order to confirm that the transit signals detected in the discovery light curve are due to a transiting planet, we obtained photometric follow-up observations of three transit events. These light curves allow us to refine the ephemeris of the system and to determine precise parameters of the system. All the photometric data are provided in Table 1 and the follow-up light curves are shown in Figure 2 along with the best-fit model and residuals.

An ingress was observed with the 0.3 m Perth Exoplanet Telescope (PEST) on 2013 March 3, using the $R_C$ filter. The photometric precision of the light curve was 5.0 mmag with a cadence of 130 s. Another ingress was observed on 2013 April 10 using the Faulkes Telescope South (FTS), which is a fully automated telescope operated as part of the Las Cumbres Observatory Global Telescope (LCOGT; Brown et al. 2013). The transit was observed in the $i$-band filter achieving a photometric precision of 1.6 mmag with a cadence of 113 s. An egress was obtained on 2013 December 21 with the multiband imager GROND (Greiner et al. 2008), mounted on the 2.2 m telescope in La Silla Observatory, using four different filters ($g$, $r$, $i$, $z$). The light curve had a precision of 1.7 mmag in the $g$ band, 1.0 mmag in $r$, 1.1 mmag in $i$, and 1.1 mmag in $z$, with a cadence of 168 s. The details of the data reduction for these facilities are described in Penev et al. (2013), Mohler-Fischer et al. (2013), and Zhou et al. (2014a).

2.2. Spectroscopic Observations

HATS-59 was spectroscopically observed between 2011 April and 2016 March to confirm the planetary nature of the transit signals and to estimate the mass and therefore the density of the planet. Furthermore, the long radial velocity (RV) monitoring of the star allowed us to detect an outer companion with a longer orbital period than the transiting planet. We present the RV used to characterize the system in Figure 5 and provide the data in Table 2.

2.2.1. Reconnaissance Spectroscopy

Reconnaissance low-resolution spectroscopic follow-up observations are important to rule out various false positive scenarios, such as a primary giant star, or large RV variations indicating that the transiting object is itself a star. Reconnaissance spectroscopic observations were carried out with WiFeS (Dopita et al. 2007), a spectrograph mounted on the ANU 2.3 m telescope. We obtained a single $R = 3000$ spectrum to estimate the stellar atmospheric parameters $T_{\text{eff}}$, [Fe/H], and $v \sin i$ and were used to confirm that the star is a dwarf. In order to rule out large RV variations (at the level of $\sim 2 \text{ km s}^{-1}$), we obtained 7 spectra with a resolution of $R = 7000$. The spectra were extracted and reduced following Bayliss et al. (2013). Another reconnaissance spectrum was obtained with the FIES spectrograph at the Nordic Optical Telescope (Telting et al. 2014), where it was reduced following Buchhave et al. (2010). We did not find large RV variations and thus ruled out the possibility that this system might be an eclipsing binary displaying a large radial velocity amplitude. We therefore proceeded with acquiring high-precision RV observations to characterize the system.

2.2.2. High-precision Radial Velocities

We carried out an intensive RV follow-up campaign to measure, with high precision, the semi-amplitude of the RV variations due to the transiting planet. The RV observations showed variations in phase with the transit ephemeris of the interior planet. They, additionally, showed evidence for a large amplitude sinusoidal variation with a period of $\sim 1400$ days. We next describe the observations and the data reduction of all the spectrographs used in this analysis.

We obtained nine spectra with the CORALIE spectrograph (Queloz et al. 2001) at the Euler 1.2 m telescope at La Silla. We also obtained five spectra with the Planet Finder Spectrograph (PFS; Crane et al. 2010) on the Magellan Clay 6.5 m telescope and seven spectra with CYCLOPS on the 3.9 m Anglo-Australian Telescope. Most of the spectra used in this analysis, most importantly for the discovery of the second outer companion, were obtained with FEROS on the MPG 2.2 m (Kaufer & Pasquini 1998) in La Silla Observatory. Twenty-four spectra were acquired with FEROS, which is a high-resolution echelle spectrograph (Kaufer & Pasquini 1998). All the spectra acquired with FEROS and CORALIE were reduced, extracted, and analyzed using the CERES pipeline (Brahm et al. 2017a). The radial velocities of the PFS spectra calibrated with an I2-cell, were computed by matching a template spectrum. For more information, we refer the reader to Butler et al. (1996). Details on
2.3. Lucky Imaging

High spatial resolution imaging were obtained as part of the follow-up campaign using the Astralux Sur camera (Hippler et al. 2009) on the New Technology Telescope (NTT), a tLa Silla Observatory in Chile. The lucky imaging observations are useful to identify close stellar companions that could affect the transit depth. The observations were carried out with the SDSS z′ filter on 2015 December 23 and reduced following Espinoza et al. (2016) but we used instead the plate scale derived in Janson et al. (2017) of 15.2 mas pixel\(^{-1}\), which is a better estimate than the one estimated in our previous work. Figure 3 shows the final reduced image and Figure 4 shows the contrast curve, where no resolved companion is detected within 2σ.

3. Analysis

3.1. Properties of the Parent Star

It is important to characterize the host star in order to measure precise planetary parameters. We used ZASPE (Brahm et al. 2017b) to get an initial estimate of the atmospheric parameters \(T_{\text{eff}}, [\text{Fe/H}], v\sin{i}, \text{and } \log g_\star\). The parameters were determined using the FEROS spectra, which
were co-added to obtain a high signal-to-noise ratio spectrum. ZASPE determines the stellar parameters via least-squares minimization against a grid of synthetic spectra in the spectral regions most sensitive to changes in the parameters (5000 Å and 6000 Å).

We then followed Sozzetti et al. (2007) to determine the fundamental stellar parameters ($M_*$, $R_*$, $L_*$, age, etc.). In particular, we used the stellar density $\rho_*$ determined from the photometric light curve, combined with the $T_{\text{eff}}$, and [Fe/H] measurements, to characterize the host star. The parameters were obtained by combining the spectroscopic and photometric parameters with the Yonsei–Yale stellar evolution models (Y2; Yi et al. 2001). This provided a revised estimate of log $g_*$, which was fixed in a second iteration of ZASPE that returned the final values of the stellar parameters.

We estimate a mass of $1.038 \pm 0.039 M_\odot$ and a radius of $1.036 \pm 0.067 R_\odot$. HATS-59 is at a reddening-corrected distance of $630 \pm 43$ pc. The distance estimated using isochrone fitting is in agreement with the distance estimated using Gaia data. Figure 6 shows the location of the star on the $T_{\text{eff}}$–$\rho_*$ diagram and the stellar parameters are provided in Table 3.

3.2. Excluding Blend Scenarios

It is important to perform a blend analysis to confirm the planetary nature of the transiting signal and to rule out a stellar eclipsing binary system as a cause of the signal. Using the photometric data, the blend analysis was carried out following Hartman et al. (2012). We find that although blended stellar eclipsing binary models can be found that fit the available photometric data, these models would produce obviously composite spectroscopic cross-correlation functions (CCFs) that are inconsistent with the observed CCFs. For example, in all cases the spectral line bisector spans (BSs) computed from the simulated CCFs have scatter in excess of 900 m s$^{-1}$, with a maximum simulated value of 4.54 km s$^{-1}$, whereas the scatter of the measured FEROS BSs is $\sim$100 m s$^{-1}$. Similarly the RVs of the simulated CCFs are in excess of 500 m s$^{-1}$, whereas the observed FEROS RVs have a scatter of 130 m s$^{-1}$ (dominated by the planetary signals). We conclude that the transiting signals are indeed due to a planet, and HATS-59 is not a blended stellar eclipsing binary.

3.3. Global Modeling of the Data

To measure the orbital and physical properties of the planets, we modeled all the photometric data (the HATSouth and follow-up photometric data) and the high-precision RV measurements following Pál et al. (2008), Bakos et al. (2010) and Hartman et al. (2012).

All the photometric light curves were modeled using the Mandel & Agol (2002) transit models with fixed quadratic limb-darkening coefficients taken from Claret (2004). For the HATSouth discovery photometric light curves, we also considered a dilution factor for the transit depth that accounts for possible blends from neighboring stars and possible over-correction introduced by the trend filtering algorithm (TFA; removes trends shared with other stars; Bakos et al. 2010; Kovács et al. 2005). As for the photometric follow-up light curves, the systematic trends were corrected by including a quadratic trend to the transit model. We also added a linear trend, with up to three parameters, to reconstruct the shape of the PSF. This trend compensates for changes in the PSF during the observations, which could be due to poor guiding, non-photometric conditions, or changes in the seeing during the transit observations.

We fit the RVs, taken with different spectrographs, with a Keplerian orbit allowing the zero-point and the RV jitter, for each instrument, to vary independently in the fit. This ensures that the best-fitting model is self-consistent with the data set. Our RVs support the existence of a second planet on top of the transiting one, and therefore models with two planets were considered in the modeling. We considered four different scenarios where one or both of the planets had a fixed circular orbit, or was allowed to have non-zero eccentricity. To choose between the different scenarios, we estimated the Bayesian evidence for each model following Weinberg et al. (2013), and
then adopted the model with the highest evidence, which we find to be a model in which the interior transiting planet has a non-zero eccentricity, while the exterior planet has a circular orbit. The evidence for this model is a modest factor of 2.4 times greater than the evidence for the model in which both planets are assumed to have circular orbits, 7 times greater than the model in which the interior planet is circular and the exterior planet has an eccentric orbit, and 19 times greater than the model in which both planets have non-zero eccentricities.

The posterior distributions for each parameter and hence the median parameters along with their 1σ uncertainties were estimated using the differential evolution Markov Chain Monte Carlo procedure (DEMCMC; ter Braak 2006) and are provided in Table 4. We find that the transiting planet HATS-59b has a mass of \(0.806 \pm 0.069 \, M_J\), a radius of \(1.126 \pm 0.077 \, R_J\), and a non-zero eccentricity of \(e = 0.129 \pm 0.049\). For the second planet, which we dub HATS-59c, we find that is well fit by a circular Keplerian orbit with \(P = 1422 \pm 14\) days, \(K = 224 \pm 14\) m s\(^{-1}\), implying a minimum mass for the companion of \(m \sin i = 12.70 \pm 0.87 \, M_J\), where \(i\) is the orbital inclination of HATS-59c.

4. Discussion

We present the discovery of HATS-59, the first multi-planet system detected by the HATSouth survey. The inner planet, HATS-59b, is a transiting hot Jupiter on an eccentric orbit, completing one revolution every \(\approx 5\) days. The outer planet, HATS-59c, is a cold massive giant planet on a circular orbit with a period of 1422 days. We note the \(m \sin i\) for HATS-59b, c is very close to the theoretical limit for deuterium burning for a solar metallicity object, and thus it may be a very low mass
brown dwarf rather than a giant exoplanet, although the distinction is unlikely to change the physical characteristics of the object.

4.1. Possible Formation Scenarios of HATS-59b,c

The architecture of HATS-59b,c poses a challenge for planet formation and migration scenarios. Can core accretion explain the presence of a hot Jupiter and a massive gas giant in the same system? Schlafman (2018) found that planets with $M > 10 M_J$ do not preferentially orbit metal-rich solar-like stars, suggesting that these objects most likely did not form via core accretion but via gravitational instability. The architecture of HATS-59b,c hence suggests that both core accretion and gravitational instability could have occurred in the same system, which was also previously suggested by Triaud et al. (2017) for WASP-53bc and WASP-81bc.

The current water iceline is around 2.92 au, suggesting that both HATS-59b and HATS-59c formed beyond the iceline and then migrated inwards to their present locations. The presence of HATS-59c, a massive companion close to the deuterium burning limit (Mollière & Mordasini 2012), could have scattered HATS-59b inwards resulting in its present eccentric orbit. Due to its mass, type-II migration is reduced even below the viscous limit for HATS-59c (Baruteau et al. 2014), resulting in only little inward migration, potentially explaining its long period.

4.2. Transit Timing Variations

Variations in the times of transits can be attributed to the presence of a secondary planet in the system (e.g., Agol et al. 2005; Mancini et al. 2016; Almenara et al. 2018). The maximum transit variation expected for the inner planet is on the order of $10^{-16}$ s, undetectable with current instruments. However, this depends on the mutual inclination between the inner and outer planet.

4.3. The Inner Transiting Planet HATS-59b

In Figure 7, we plot the masses and radii of all the transiting exoplanets having these parameters measured with a precision better than 20%. HATS-59b lies in a densely populated region of the parameter space, where numerous non inflated giant
planets with similar properties have been detected. In terms of structure, HATS-59b is similar to HAT-P-29 b (M_p = 0.78 M_J, R_p = 1.11 R_J, and P = 5.7 days; Buchhave et al. 2011); and K2-115 b, (M_p = 0.84 M_J, R_p = 1.12 R_J, and P = 20.3 days; Shporer et al. 2017), however with a significantly shorter period.

We compare the mass and radius of HATS-59b to the theoretical models of Fortney et al. (2007), for a hydrogen–helium dominated planets with different core masses, at a distance of 0.045 au, and an age of 4.3 Gyr. We find that its composition is consistent with a gas-dominated planet with a core mass M_c < 25 M_⊕. However, these models assume that all the solid material is located inside the core. According to Thorngren et al. (2016), HATS-59b could have a larger amount of heavy elements in its interior (∼50 M_⊕) if they are predominantly mixed in the gaseous envelope.

4.3.1. Possible Migration Scenarios of HATS-59b

Hot Jupiters are thought to form beyond the ice line and migrate inwards via disk or high eccentricity migration, where the latter requires an outer planetary or stellar companion.

Observations of the projected spin–orbit angle via the Rossiter–McLaughin (RM) effect provides an approach to distinguish between these migration scenarios. Disk migration predicts circular and aligned orbits, whereas the high eccentricity migration can produce a broad range of obliquities, depending mostly on the scattering mechanism and on the effectiveness of tidal interactions at damping obliquities.

The amplitude of the RM effect scales with v sin i, the projected rotational velocity of the star. We predict an RM amplitude of 23–36 m s⁻¹ for v sin i = 2.2–3.4 km s⁻¹. Measuring the RM amplitude for this faint star (V = 13.951 ± 0.030 mag), is challenging but plausible using HIRES (Vogt et al. 1994; Wang et al. 2018) on the Keck telescope or with the new high-resolution spectrograph, ESPRESSO (Pepe et al. 2014) at the Very Large Telescope.

Disk migration predicts that planets can migrate up until they reach the planet-star Roche separation (a_rosech), the critical distance within which a planet would start losing mass (Faber et al. 2005). On the other hand, high-eccentricity migration predicts planets will circularize at a semimajor axis greater than 2a_rosech. This mechanism would require that hot Jupiters are excited to eccentric orbits, often by being scattered by a distant
massive companion, and survived the tidal dissipation process required to circularize their final orbits (Faber et al. 2005; Ford 2006).

Many distant planetary companions to hot Jupiters have been detected (Knutson et al. 2014). In Figure 8, we show planetary mass plotted against a/a_{roche}, where

\[ a_{roche} = 2.7R_p \left( \frac{M_*}{M_p} \right)^{1/3}, \]

for all hot Jupiters whose mass and radii are determined with a precision better than 30% (small gray circles). Blue circles show all the hot Jupiters with a fully resolved orbit of the outer planetary companion and green triangle represent the systems whose RVs show a linear trend, taken from Knutson et al. (2014). The position of HATS-59b is shown with a red square. All but one multi-planet system have a/a_{roche} > 2, HAT-P-7b, with a value a/a_{roche} only slightly lower than 2. The available data on hot Jupiters with companions indicate that high eccentricity migration could be the main mechanism for placing the gas giant on a close-in orbit in these systems.

We compare the parameters of HATS-59c to all the detected planetary companions whose orbit is fully resolved. Figure 9

| Parameter | HATS-59b Value | HATS-59c Value |
|-----------|----------------|----------------|
| Light curve parameters | | |
| \( P \) (days) | 5.416081 ± 0.000016 | 1422 ± 14 |
| \( T_c \) (BJD) \( ^b \) | 2456260.66527 ± 0.00052 | 2456252 ± 11 |
| \( T_{14} \) (days) \( ^b \) | 0.1497 ± 0.0017 | 0.957 ± 0.054 |
| \( T_2 = T_4 \) (days) \( ^b \) | 0.0186 ± 0.0016 | 0.0863 ± 0.0011 |
| \( a/R_c \) | 12.66 ± 0.77 | 518 ± 32 |
| \( \zeta/R_c \) \( ^e \) | 15.23 ± 0.13 | ... |
| \( R_p/R_c \) | 0.1116 ± 0.0021 | ... |
| \( b^2 \) | 0.2096 ± 0.0064 | ... |
| \( b \equiv a \cos i/R_c \) | 0.4577 ± 0.0066 | ... |
| \( i \) (deg) | 88.10 ± 0.33 | ... |
| Limb-darkening coefficients \( ^d \) | | |
| \( c_1 \), \( g \) (linear term) | 0.5965 | ... |
| \( c_2 \), \( g \) (quadratic term) | 0.2045 | ... |
| \( c_3 \), \( R \) | 0.3628 | ... |
| \( c_4 \), \( R \) | 0.3129 | ... |
| \( c_5 \), \( R \) | 0.3896 | ... |
| \( c_0 \), \( R \) | 0.3085 | ... |
| \( c_6 \), \( i \) | 0.2930 | ... |
| \( c_7 \), \( z \) | 0.3208 | ... |
| \( c_8 \), \( z \) | 0.2259 | ... |
| \( c_9 \), \( z \) | 0.3232 | ... |
| RV parameters | | |
| \( K \) (m \( \text{s} ^{-1} \)) | 92.1 ± 7.8 | 224 ± 14 |
| \( e^f \) | 0.129 ± 0.049 | <0.083 |
| \( \omega \) | 227 ± 29 | ... |
| \( \sqrt{e} \cos \omega \) | −0.233 ± 0.084 | ... |
| \( \sqrt{e} \sin \omega \) | −0.25 ± 0.11 | ... |
| \( e \cos \omega \) | −0.082 ± 0.034 | ... |
| \( e \sin \omega \) | −0.090 ± 0.065 | ... |
| CORALIE RV jitter (m \( \text{s} ^{-1} \)) | <20.7 | ... |
| FEROS RV jitter (m \( \text{s} ^{-1} \)) | 58 ± 44 | ... |
| CORALIE RV jitter (m \( \text{s} ^{-1} \)) | 24 ± 14 | ... |
| CYCLOPS RV jitter (m \( \text{s} ^{-1} \)) | 93 ± 40 | ... |
| Planetary parameters | | |
| \( M_p \) (\( M_J \)) | 0.806 ± 0.069 | ... |
| \( M_p \sin i \) (\( M_J \)) | 12.70 ± 0.87 | ... |
| \( R_p \) (\( R_J \)) | 1.126 ± 0.077 | ... |
| \( C(M_p, R_p) \) \( ^g \) | 0.05 | ... |
| \( \rho_p \) (g \( \text{cm} ^{-3} \)) | 0.70 ± 0.16 | ... |
| \( \log g_p \) (cgs) | 3.195 ± 0.069 | ... |
| \( a \) (au) | 0.06112 ± 0.00076 | 2.504 ± 0.035 |
| \( T_{90} \) (K) \( ^h \) | 1128 ± 40 | 175.9 ± 6.4 |

| Parameter | HATS-59b Value | HATS-59c Value |
|-----------|----------------|----------------|
| Mass ratio | 0.0841 ± 0.0093 | ... |
| \( \langle P \rangle \) (erg \( \text{s} ^{-1} \) cm\(^{-2} \)) | (3.66 ± 0.53) \( \times 10^8 \) | (2.16 ± 0.32) \( \times 10^5 \) |

Notes.

\( ^a \) We provide the median value and the 68.3% (1\( \sigma \)) confidence intervals for all the parameters. Reported results assume an eccentric orbit for HATS-59b and a circular orbit for HATS-59c.

\( ^b \) Reported times are in Barycentric Julian Date calculated directly from UTC, without correction for leap seconds. \( T_c \): Reference epoch of mid transit that minimizes the correlation with the orbital period. Note that HATS-59c has not been observed to transit. We list here the time of mid transit, implied by the orbital solution, in the event that the orbital inclination permits transits. \( T_{14} \): total orbit duration, time between first to last contact; \( T_{14} = T_{14} \): ingress/egress time, time between first and second, or third and fourth contact. For HATS-59c \( T_{14} \) and \( T_2 \) are calculated assuming central transits (\( i = 90^\circ \) orbit) and a Jupiter radius for the planet.

\( ^c \) Reciprocal of the half duration of the transit used as a jump parameter in our MCMC analysis in place of \( a/R_c \). It is related to \( a/R_c \), by the expression \( \sqrt{R_c} = a/R_c (2\pi(1 + e \sin \omega))/\sqrt{1 - b^2} \) (Bakos et al. 2010).

\( ^d \) Values for a quadratic law, adopted from the tabulations by Claret (2004) according to the spectroscopic (ZASPE) parameters listed in Table 3.

\( ^e \) For HATS-59c, we list the 95% confidence upper-limit on the eccentricity. All the other parameters are estimated assuming a circular orbit for this planet.

\( ^f \) Astrophysical or instrumental error added in quadrature to the original RV errors. This term is varied in the fit independently for each instrument assuming a prior that is inversely proportional to the jitter.

\( ^g \) Correlation coefficient between the planetary mass \( M_p \) and radius \( R_p \) determined from the parameter posterior distribution via \( C(M_p, R_p) = \langle (M_p - \langle M_p \rangle)(R_p - \langle R_p \rangle) \rangle/\sigma_{M_p}\sigma_{R_p} \), where \( \langle \cdot \rangle \) is the expectation value, and \( \sigma \) is the std. dev. of \( x \).

\( ^h \) Planet equilibrium temperature averaged over the orbit, calculated assuming a Bond albedo of zero, and that flux is reradiated from the full planet surface.

\( ^i \) The Saffronov number is given by \( \Theta = \left( \frac{1}{2} V_{esc}^2 / V_{th}^2 \right) = (a/R_C)(M_p/M_J) \) (see Hansen & Barman 2007).

\( ^j \) Incoming flux per unit surface area, averaged over the orbit.

Table 5

| Date (UT) | Sun RA distance (hr) |
|-----------|----------------------|
| 2021 May 30 | 6.8 |
| 2025 Apr 21 | 9.4 |
| 2029 Mar 13 | 12.2 |
shows the position of HATS-59c (red square) on the minimum mass-period diagram with the other discovered companions (blue circles). With a period of 1422 days, HATS-59c has the third longest period, indicating how few outer companions to transiting hot Jupiters have been characterized due to the lack of RV follow-up observations. All of the companions have minimum masses above 1 \( M_J \), which is most likely due to selection effects with a detection limit of \( \sim 20 \) m \( s^{-1} \) for a planet orbiting a Sun analog.

### 4.4. Possible Transits of HATS-59c

As was stated in the previous section, knowing the mutual inclination between HATS-59b and HATS-59c can be useful to further clarify the possible migration path of this system. The host star is too faint for the GAIA mission to be able to measure the astrometric signal of HATS-59c. However, the inclination of HATS-59c with respect to the plane of the sky could be measured if it also transits its star. While the a priori probability of transit for HATS-59c is \( \sim 0.2\% \), if we consider that the two planets are co-planar, then the probability of transit raises by one order of magnitude. Figure 10 shows the transit probability of HATS-59c for different assumed maximum mutual inclinations \( (\delta) \) between the orbital plane of the planets. The probabilities were computed following the formalism of Beatty & Seager (2010). The maximum probability (3.8\%) occurs if the mutual inclination between the planets is around 3 deg.

The future transit windows for HATS-59c are listed in Table 5. In this table, we indicate the center of the transit window and the edges support from FONDECYT project 1171208, BASAL MRI grant NSF/AST-0723074, operations have been supported by NASA grants NNX09AB29G, NNX12AH91H, and NNX17AB61G, and follow-up observations receive partial support from grant NSF/AST-1108686. P.S. would like to thank Bertram Bitsch for useful discussions. A.J. acknowledges support from FONDECYT project 1171208, BASAL, and Analysis Consortium (DPAC, https://www.cosmos.esa.int/web/gaia/dpac/consortium). Funding for the DPAC has been provided by national institutions, in particular the institutions participating in the GAIA Multilateral Agreement. This work is based on observations made with ESO Telescopes at the La Silla Observatory. This paper also uses observations obtained with facilities of the Las Cumbres Observatory.

We acknowledge the use of the AAVSO Photometric All-Sky Survey (APASS), funded by the Robert Martin Ayers Sciences Fund, and the SIMBAD database, operated at CDS, Strasbourg, France. Operations at the MPG 2.2 m Telescope are jointly performed by the Max Planck Gesellschaft and the European Southern Observatory. The imaging system GROND has been built by the high-energy group of MPE in collaboration with the LSW Tautenburg and ESO. We thank the MPG 2.2 m telescope support team for their technical assistance during observations.

### ORCID iDs

P. Sarkis ⎼ https://orcid.org/0000-0001-8128-3126
J. D. Hartman ⎼ https://orcid.org/0000-0001-8732-6166
G. Á. Bakos ⎼ https://orcid.org/0000-0001-7204-6727
R. Brahms ⎼ https://orcid.org/0000-0002-9158-7315
D. Bayliss ⎼ https://orcid.org/0000-0001-6023-1335
L. Mancini ⎼ https://orcid.org/0000-0002-9428-8732
W. Bhatti ⎼ https://orcid.org/0000-0002-0628-0088
K. Penev ⎼ https://orcid.org/0000-0003-4464-1371
P. Arriagada ⎼ https://orcid.org/0000-0002-3578-551X
R. P. Butler ⎼ https://orcid.org/0000-0003-1305-3761
J. D. Crane ⎼ https://orcid.org/0000-0002-5226-787X
C. G. Tinney ⎼ https://orcid.org/0000-0002-7595-0970
S. Durkan ⎼ https://orcid.org/0000-0002-3663-3251
V. Suc ⎼ https://orcid.org/0000-0001-7070-3842
L. A. Buchhave ⎼ https://orcid.org/0000-0003-1605-5666

### References

Agol, E., Steffen, J., Sari, R., & Clarkson, W. 2005, MNRAS, 359, 567
Almenara, J. M., Diaz, R. F., Hebrard, G., et al. 2018, A&A, 615, A90
Artyomowicz, P. 1993, ApJ, 419, 166
Bakos, G. Á, Csubry, Z., Penev, K., et al. 2013, PASP, 125, 154
Bakos, G. Á, Howard, A. W., Noyes, R. W., et al. 2009, ApJ, 707, 446
Bakos, G. Á, Torres, G., Pál, A., et al. 2010, ApJ, 710, 1724
Baruteau, C., Crida, A., Paardekooper, S.-J., et al. 2014, in Protostars and Planets VI, ed. H. Beuther et al. (Tucson, AZ: Univ. Arizona Press), 667
Batygin, K., Bodenheimer, P., & Laughlin, G. 2009, ApJL, 704, L49
Bayliss, D., Zhou, G., Penev, K., et al. 2013, AJ, 146, 113
Beatty, T. G., & Seager, S. 2010, AJ, 712, 1433
Becker, J. C., Vanderburg, A., Adams, F. C., Rappaport, S. A., & Schwengeler, H. M. 2015, ApJL, 812, L18
Brahm, R., Jordan, A., & Espinoza, N. 2017a, PASP, 129, 034002
Brahm, R., Jordan, A., Hartman, J., & Bakos, G. 2017b, MNRAS, 467, 971
Brown, T. M., Baliber, N., Bianco, F. B., et al. 2013, PASP, 125, 1031
Buchhave, L. A., Bakos, G. Á, Hartman, J. D., et al. 2010, ApJ, 720, 1118
Buchhave, L. A., Bakos, G. Á, Hartman, J. D., et al. 2011, ApJ, 733, 116
Buehler, P. B., Knutson, H. A., Batygin, K., et al. 2016, ApJ, 821, 26
Butler, R. P., Marcy, G. W., Williams, E., et al. 1996, PASP, 108, 500
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Claret, A. 2004, A&A, 428, 1001
Crane, J. D., Shectman, S. A., Butler, R. P., et al. 2010, Proc. SPIE, 7735, 773553
Dopita, M., Hart, J., McGregor, G., et al. 2007, ApSS, 310, 255
Endl, M., Caldwell, D. A., Barclay, T., et al. 2014, ApJ, 795, 151
Espinoza, N., Bayliss, D., Hartman, J. D., et al. 2016, AJ, 152, 108
Faber, J. A., Rasio, F. A., & Willems, B. 2005, Icar, 175, 248
Ford, E. B. 2006, ApJ, 642, 505
Fortney, J. J., Marley, M. S., & Barnes, J. W. 2007, ApJ, 659, 1661
Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425
Greiner, J., Bomemann, W., Clemens, C., et al. 2008, PASP, 120, 405
Hansen, B. M. S., & Barman, T. 2007, ApJ, 671, 861
Hardy, R. A., Harrington, J., Hardin, M. R., et al. 2017, ApJ, 836, 143
Hartman, J. D., Bayliss, D., Brahm, R., et al. 2015, AJ, 149, 166
Hartman, J. D., Bakos, G. A, Béky, B., et al. 2012, AJ, 144, 139
Hellier, C., Anderson, D. R., Collier Cameron, A., et al. 2012, MNRAS, 426, 739
Hippler, S., Bergfors, C., Wolfgang, B., et al. 2009, Msngr, 137, 14
Howard, A. W., Marcy, G. W., Bryson, S. T., et al. 2012, ApJS, 201, 15
Janson, M., Durkan, S., Hippler, S., et al. 2017, A&A, 599, A70
Jin, S., & Mordasini, C. 2018, ApJ, 853, 163
Jordán, A., Brahm, R., Bakos, G. Á., et al. 2014, AJ, 148, 29
Kaufer, A., & Pasquini, L. 1998, Proc. SPIE, 3355, 844
Knutson, H. A., Fulton, B. J., Montet, B. T., et al. 2014, ApJ, 785, 126
Kovács, G., Bakos, G., & Noyes, R. W. 2005, MNRAS, 356, 557
Kovács, G., Zucker, S., & Mazeh, T. 2002, A&A, 391, 369
Kozai, Y. 1962, AJ, 67, 591
Li, G., Naoz, S., Kocsis, B., & Loeb, A. 2014, ApJ, 785, 116
Lidov, M. L. 1962, P&SS, 9, 719
Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Natur, 380, 606
Mancini, L., Lillo-Box, J., Southworth, J., et al. 2016, A&A, 590, A112
Mandel, K., & Agol, E. 2002, ApJL, 580, L171
Mohler-Fischer, M., Mancini, L., Hartman, J. D., et al. 2013, A&A, 558, A55
Mollière, P., & Mordasini, C. 2012, A&A, 547, A105
Mordasini, C., van Boekel, R., Mollière, P., Henning, T., & Benneke, B. 2016, ApJ, 832, 41
Nagasawa, M., Ida, S., & Bessho, T. 2008, ApJ, 678, 498
Neveu-VanMalle, M., Queloz, D., Anderson, D. R., et al. 2016, A&A, 586, A93
Ngo, H., Knutson, H. A., Hinkley, S., et al. 2015, ApJ, 800, 138
Pál, Á., Bakos, G. Á., Torres, G., et al. 2008, ApJ, 680, 1450
Penev, K., Bakos, G. Á, Bayliss, D., et al. 2013, AJ, 145, 5
Pepe, F., Ehrenreich, D., & Meyer. M. R. 2014, Natur, 513, 358
Petrovich, C. 2015, ApJ, 805, 75
Queloz, D., Eggenberger, A., Mayor, M., et al. 2000, A&A, 359, L13
Queloz, D., Mayor, M., Udry, S., et al. 2001, Msngr, 105, 1
Rabus, M., Alonso, R., Belmonte, J. A., et al. 2009, A&A, 494, 391
Schlaufman, K. C. 2018, ApJ, 853, 37
Shporer, A., Zhou, G., Fulton, B. J., et al. 2017, AJ, 154, 188
Sozzetti, A., Torres, G., Charbonneau, D., et al. 2007, ApJ, 664, 1190
Telting, J. H., Avila, G., Buchhave, L., et al. 2014, AN, 335, 41
Ter Braak, C. J. F. 2006, Statistics and Computing, 16, 239
Thorngren, D. P., Fortney, J. J., Murray-Clay, R. A., & Lopez, E. D. 2016, ApJ, 831, 64
Triaud, A. H. M. J., Neveu-VanMalle, M., Lendl, M., et al. 2017, MNRAS, 467, 1714
Vogt, S. S., Allen, S. L., Bigelow, B. C., et al. 1994, Proc. SPIE, 2198, 362
Wang, S., Addison, B., Fischer, D. A., et al. 2018, AJ, 155, 70
Weinberg, M. D., Yoon, I., & Katz, N. 2013, arXiv:1301.3156
Winn, J. N., & Fabrycky, D. C. 2015, ARA&A, 53, 409
Yi, S., Demarque, P., Kim, Y.-C., et al. 2001, ApJS, 136, 417
Zhou, G., Bayliss, D., Hartman, J. D., et al. 2014a, MNRAS, 437, 2831
Zhou, G., Bayliss, D., Hartman, J. D., et al. 2015, ApJL, 814, L16
Zhou, G., Bayliss, D., Penev, K., et al. 2014b, AJ, 147, 144