

NGTS 15b, 16b, 17b, and 18b: four hot Jupiters from the Next-Generation Transit Survey

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ABSTRACT

We report the discovery of four new hot Jupiters with the Next-Generation Transit Survey (NGTS). NGTS-15b, NGTS-16b, NGTS-17b, and NGTS-18b are short-period ($P < 5$ d) planets orbiting G-type main-sequence stars, with radii and masses between 1.10 and $1.30R_J$ and 0.41 and $0.76M_J$, respectively. By considering the host star luminosities and the planets' small orbital separations (0.039 – 0.052 au), we find that all four hot Jupiters are highly irradiated and therefore occupy a region of parameter space in which planetary inflation mechanisms become effective. Comparison with statistical studies and a consideration of the planets' high incident fluxes reveal that NGTS-16b, NGTS-17b, and NGTS-18b are indeed likely inflated, although some disparities arise upon analysis with current Bayesian inflationary models. However, the underlying relationships that govern radius inflation remain poorly understood. We postulate that the inclusion of additional hyperparameters to describe latent factors such as heavy element fraction, as well as the addition of an updated catalogue of hot Jupiters, would refine inflationary models, thus furthering our understanding of the physical processes that give rise to inflated planets.

Key words: planetary systems – planets and satellites: detection – planets and satellites: gaseous planets.

1 INTRODUCTION

The field of exoplanet discovery has uncovered a cosmic zoo of planetary types that extends far beyond those of our Solar system. As some of the first exoplanets ever detected, a particularly immediate revelation was the existence of Jupiter-sized planets on extremely short orbits ($P < 10$ d; e.g. Mayor & Queloz 1995; Charbonneau

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et al. 2000; Henry et al. 2000). In spite of their apparent rarity, comprising only <1 per cent of systems (Mayor et al. 2011; Wright et al. 2012; Fressin et al. 2013; Hsu et al. 2019), these ‘hot Jupiters’ are some of the most easily detectable exoplanets, as their large radii produce transits that are well above typical telescope noise limits, and their large masses and short orbital periods yield large radial velocity signals.

A distinctive yet poorly understood feature of the hot Jupiter population is the observation that many of these planets have radii that are larger than expected from theoretical models (e.g. Guillot & Showman 2002; Anderson et al. 2011; Hartman et al. 2012; Espinoza et al. 2016; Raynard et al. 2018). While this feature appears to correlate with incident flux (Laughlin, Crismani & Adams 2011; Weiss et al. 2013; Thorngren & Fortney 2018), this alone does not provide a sufficient explanation for inflation, and thus the underlying driving mechanisms continue to be debated (see e.g. Spiegel & Burrows 2013, for a comprehensive review). Indeed, evolutionary models that incorporate stellar irradiation and heavy metals can explain the unexpected radii of some hot Jupiters (Fortney, Marley & Barnes 2007; Baraffe, Chabrier & Barman 2008), but are yet to adequately describe the high-irradiation regime.

Efforts to characterize the relationship between inflation and incident flux have nevertheless provided valuable insight into the topic. In particular, the physical processes that cause inflation are believed to become effective in planets that are irradiated at fluxes in excess of $\sim 2 \times 10^5 \text{ W m}^{-2}$ (Demory & Seager 2011; Miller & Fortney 2011). Furthermore, a recent study by Sestovic, Demory & Queloz (2018) suggests that above an incident flux of $\sim 1.6 \times 10^6 \text{ W m}^{-2}$, all hot Jupiters in the mass range of $0.37\text{--}0.98 M_J$ appear inflated. For statistical studies such as this, increasing the sample of well-characterized hot Jupiters is crucial, and allows us to further constrain and parametrize inflation mechanisms, which remain poorly understood.

In this paper, we report the discovery of four new hot Jupiter planets from the Next-Generation Transit Survey (NGTS), three of which appear inflated. In Section 2, we describe the discovery photometry from NGTS and the subsequent photometric and radial velocity follow-up observations. In Section 3, we present our analysis of these data, including the determination of both the stellar and planetary parameters from spectral analysis, spectral energy distribution (SED) fitting, and global modelling. An investigation into the inflation of each planet is covered in Section 4, with the subsequent results being discussed in Section 5. Finally, our conclusions are laid out in Section 6. NGTS-15b, NGTS-16b, NGTS-17b, and NGTS-18b bring the total planet count from NGTS to 17 (note that NGTS-7Ab is a brown dwarf).

2 OBSERVATIONS

2.1 NGTS discovery photometry

NGTS-15 to NGTS-18 were initially identified as transiting exoplanet candidate systems from photometry from the NGTS (Wheatley et al. 2018), a ground-based wide-field exoplanet survey. Based at ESO’s Paranal observatory in Chile, NGTS consists of an array of 12 independently mounted 20-cm Newtonian telescopes, each equipped with a $2K \times 2K$ deep-depleted Andor iKon-L CCD camera. The custom NGTS 520–890-nm filter optimizes the survey for studies of K and M dwarf stars that, due to their small radii, provide the best opportunity for discovering small transiting planets.

Table 1. NGTS photometry for each object. The full tables are available in a machine-readable format from the online journal. A portion is shown here for guidance.

Time (BJD-2450000)	Flux (Normalized)	Flux Error
(a) NGTS photometry for NGTS-15		
7982.8536	0.973	0.031
7982.8538	0.973	0.031
7982.8539	1.001	0.031
7982.8541	1.008	0.031
7982.8542	1.023	0.031
...
8195.5583	1.012	0.030
8195.5584	1.039	0.030
8195.5586	0.974	0.030
8195.5587	0.959	0.030
8195.5589	1.025	0.030
(b) NGTS photometry for NGTS-16		
7981.7857	1.010	0.031
7981.7860	0.968	0.031
7981.7862	0.985	0.031
7981.7863	1.007	0.031
7981.7865	1.008	0.031
...
8191.5306	1.020	0.027
8191.5307	0.969	0.027
8191.5308	0.993	0.027
8191.5310	0.994	0.027
8191.5311	0.991	0.027
(c) NGTS photometry for NGTS-17		
7982.8537	1.001	0.025
7982.8539	1.021	0.025
7982.8540	1.014	0.025
7982.8542	1.002	0.025
7982.8543	1.023	0.025
...
8195.5583	0.927	0.025
8195.5584	0.997	0.025
8195.5586	1.032	0.025
8195.5587	0.984	0.025
8195.5589	1.025	0.025
(d) NGTS photometry for NGTS-18		
8097.8232	1.016	0.032
8097.8233	0.961	0.032
8097.8235	0.977	0.032
8097.8236	1.007	0.032
8097.8238	1.005	0.032
...
8334.5046	1.000	0.033
8334.5047	0.991	0.033
8334.5049	1.010	0.033
8334.5050	1.026	0.033
8334.5052	0.983	0.033

NGTS-15, NGTS-16, and NGTS-17 were observed during the 2017 observing campaign for 160, 137, and 160 nights, respectively, between 2017 August 16 and 2018 March 18. NGTS-18 was observed the following season for 165 nights over the period of 2017 December 10 to 2018 August 7. Over 188 000 images were collected for each object using a single NGTS telescope with 10-s exposures (see Table 1 for an excerpt of the NGTS photometry for each object; see Table 2 for further details).

Table 2. Summary of photometric observations.

Target	Instrument	Night(s) observed	N_{images}	Exp. time (s)	Filter	Comments
NGTS-15	NGTS	16/08/17–18/03/18	196 732	10	NGTS	–
	SAAO	21/11/18	285	60	I	–
	SAAO	06/12/19	276	30	I	–
NGTS-16	NGTS	16/08/17–18/03/18	188 417	10	NGTS	–
	TESS	19/10/18–14/11/18	831	1800 ^a	TESS	Sector 4
	SAAO 1.0m	21/12/18	200	60	I	–
	SAAO 1.0m	05/12/19	540	30	I	–
NGTS-17	NGTS	16/08/17–18/03/18	196 732	10	NGTS	–
	TESS	15/11/18–11/12/18	1093	1800 ^a	TESS	Sector 5
	SAAO 1.0m	05/02/19	1104	15	I	–
NGTS-18	NGTS	10/12/17–07/08/18	243 515	10	NGTS	–
	SAAO 1.0m	21/03/19	598	20	I	–
	TESS	26/03/19–22/04/19	1017	1800 ^a	TESS	Sector 10
	Lesedi	24/06/2020	426	15	I	–
	Lesedi	30/06/2020	550	15	V	–

Notes. The NGTS filter has a bandpass from 520 to 890 nm; the *TESS* bandpass spans 600–1000 nm.

^a*TESS* cameras have an exposure time of 2 s but are stacked to a 30-min cadence.

The data were reduced and aperture photometry performed via the CASUTOOLS package,¹ before being detrended using an optimized version of the SysRem algorithm (Tamuz, Mazeh & Zucker 2005) that has been adapted for the NGTS pipeline. The data were then searched for transit-like events by ORION (Wheatley et al. 2018), a custom implementation of the BLS fitting algorithm (Kovács, Zucker & Mazeh 2002). ORION identified eight partial and three full transits for NGTS-15; four partial and four full transits for NGTS-16; fifteen partial transits for NGTS-17; and sixteen partial and four full transits for NGTS-18. Light curves of the NGTS detections, phase folded on the best-fitting period, are shown in Fig. 1. The initial fits to the NGTS data provided by ORION revealed that the depths, widths, and shapes of the transits for each object were compatible with transiting hot Jupiter planets. In addition, a convolutional neural network applied to the NGTS data found that the probabilities of each light curve containing a transiting exoplanet were all greater than 0.95, consistent with previous confirmed NGTS planet discoveries (Chaushev et al. 2019).

In order to rule out the possibility that any of our detected companions were stellar rather than planetary, we performed additional checks on the NGTS data. The phase-folded light curves for each object were searched for any evidence of a secondary eclipse around phase 0.5 that would indicate the presence of a second star. Furthermore, we compared the transit depth of consecutive odd and even transits to check for a depth difference consistent with an eclipsing binary star system that had been mis-folded on half the true period. For all four targets, we find no indication in the NGTS photometry to suggest that the companions were not planets.

2.2 Additional photometry

In order to confirm that each stellar companion was indeed a planet, and to constrain the transit parameters, we obtained additional photometry with the 1.0-m and Lesedi telescopes at the South African Astronomical Observatory (SAAO). For three of the candidates, we were also able to use data from the *Transiting Exoplanet Survey*

Satellite (*TESS*; Ricker et al. 2014). The details of this additional photometry are outlined below.

2.2.1 TESS

TESS is a space-based NASA survey telescope that searches for transiting planets around bright stars (Ricker et al. 2014). It has a wide field of view, with four $24 \times 24^\circ$ cameras, each equipped with four $2k \times 2k$ CCDs. Its typical observing baseline of 27 d makes it well suited to detecting short-period transiting exoplanets.

We searched for our candidates in the *TESS* full-frame images (FFIs) using the TESSCut² tool and found that NGTS-16 and NGTS-17 were observed in *TESS* Sectors 4 and 5, respectively, each for 27 consecutive nights between 2018 October 19 and 2018 December 11. In addition, NGTS-18 was observed between 2019 March 26 and 2019 April 22 in *TESS* Sector 10. NGTS-15 falls on a CCD in *TESS* Sector 5, but unfortunately into the overscan region of the camera rather than the science pixels, and therefore there is no *TESS* FFI observation for this star. A summary of this information can be found in Table 2.

Each star in the *TESS* FFIs was observed at 30-min cadence, and for each of our candidates we used an automatically determined optimal aperture to exclude neighbouring stars. These aperture sizes ranged from three to eight pixels. However, the large pixel scale of *TESS* (21 arcsec) meant that there was still some slight contamination of the FFI light curves, which we account for in our analysis (see Section 3.2).

For each candidate, we found that the best BLS period from *TESS* was consistent with the ORION value for the NGTS photometry. *TESS* detected three full and two partial transits for NGTS-16, eight full partial transits for NGTS-17, and seven full transits for NGTS-18. Phase-folded light curves of the *TESS* data can be found in Fig. 1.

2.2.2 SAAO

Between 2018 November and 2019 December, we took at least one set of follow-up photometry for each target using the

¹<http://casu.ast.cam.ac.uk/surveys-projects/software-release>

²<https://mast.stsci.edu/tesscut/>

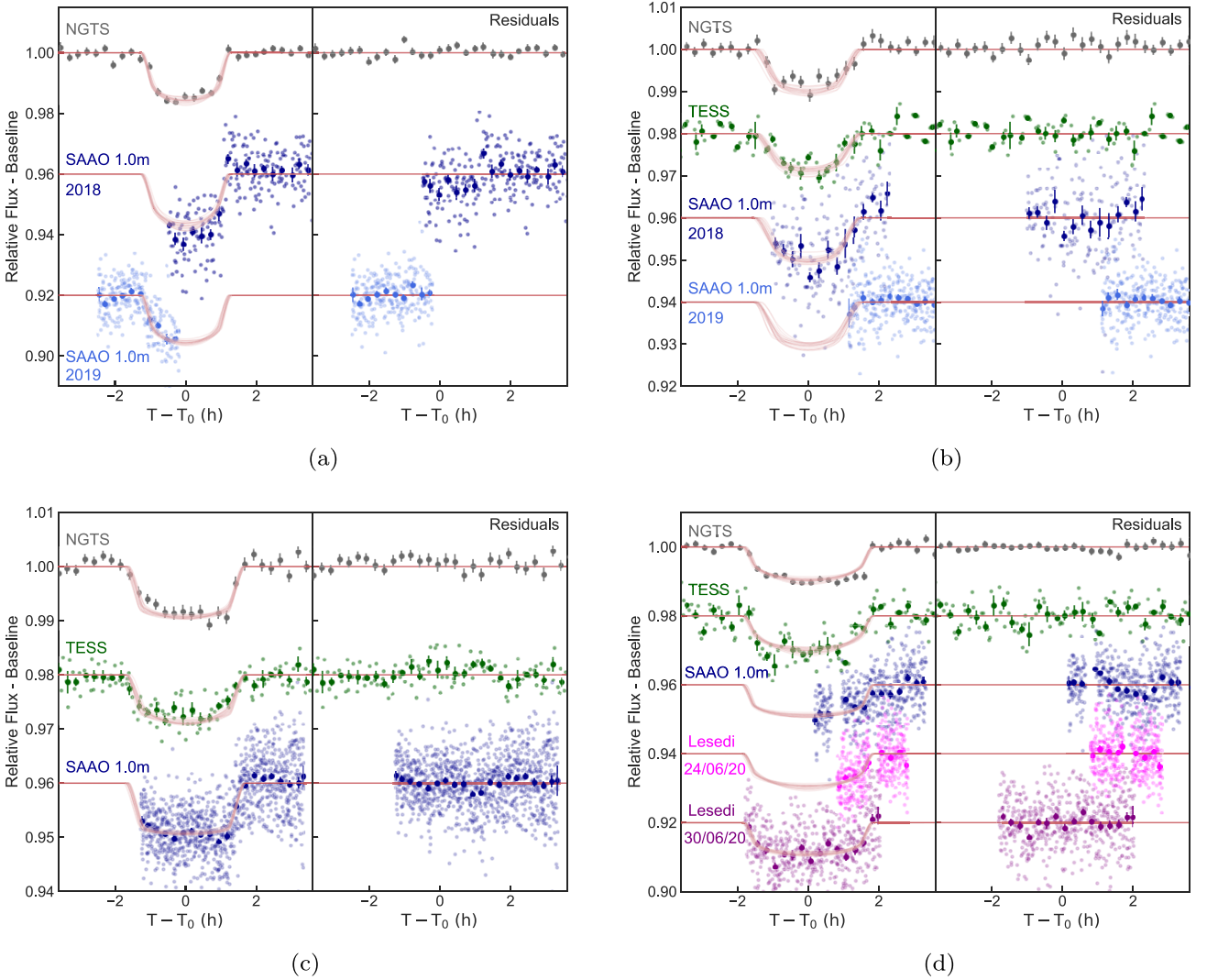


Figure 1. NGTS discovery photometry (grey points) and follow-up photometry (*TESS*: green points, SAAO 1.0-m telescope *I* band: dark and light blue points, Lesedi *I* band: pink points, Lesedi *V* band: purple points) for each planet. Note that, for clarity, we exclude the unbinned NGTS data from the plots. The red lines show 20 light-curve models generated from randomly drawn posterior samples of the ALLESFITTER fit. Residuals are shown to the right of the light curves. (a) Photometry for NGTS-15b. The NGTS discovery light curve is phase folded at the best-fitting period of $3.276\,23 \pm 0.000\,01$ d. The light curves from the 1.0-m telescope at SAAO show a detection of egress from 2018 November 21 and a detection of ingress from 2019 December 6. Note that the in-transit scatter during the 2018 observation is a result of poor atmospheric conditions, and that the transit depths from global modelling for the NGTS and SAAO light curves agree to within errors. (b) Photometry for NGTS-16b. The NGTS and *TESS* light curves are phase folded on the best-fitting period, $4.845\,32 \pm 0.000\,02$ d. For this object, we obtained two light curves with the SAAO 1.0-m telescope on 2018 December 21 and 2019 December 5, both of which include egress. As with NGTS-15, the large in-transit scatter of the SAAO light curve from 2018 is due to poor atmospheric conditions and the true errors of these data points are likely underestimated. All four transit depths from the global modelling agree to within errors. (c) Photometry for NGTS-17b. The NGTS discovery light curve and *TESS* follow-up light curve are phase folded at the best-fitting period of $3.242\,53 \pm 0.000\,01$ d. The SAAO light curve consists of one data set from 2019 February 5. (d) Photometry for NGTS-18b. The NGTS discovery light curve and *TESS* follow-up light curve are phase folded at the best-fitting period of $3.051\,25 \pm 0.000\,01$ d. The SAAO 1.0-m telescope light curve consists of one data set from 2019 March 21; although egress is seen, due to the poor quality of the data, we omit it from our global modelling. The two Lesedi data sets in the *I* and *V* bands comprise of single observations from June 24 and 30, respectively.

1.0-m telescope at SAAO. The telescope was equipped with the full-frame transfer CCD Sutherland High-speed Optical Camera (SHOC), ‘*SHOC’n’awe*’, and all observations were taken using the *I*-band filter. The $2.85\text{ arcmin} \times 2.85\text{ arcmin}$ field of view of *SHOC’n’awe* on the 1.0-m telescope allowed us to simultaneously observe at least one comparison star of similar brightness for each object.

For NGTS-18, we also had the opportunity to obtain two light curves using the newly commissioned 1.0-m Lesedi telescope at SAAO, which was equipped with the ‘*SHOC’n’disbelief*’ optical

camera. The instrument’s slightly wider field of view ($5.7\text{ arcmin} \times 5.7\text{ arcmin}$) allowed for an increased selection of comparison stars.

Two light curves of NGTS-15 were obtained using the 1.0-m telescope on the nights of 2018 November 21 and 2019 December 6 with exposure times of 60 and 30 s, respectively. We obtained 285 images for the 2018 data, and truncated the 2019 data from 543 to 276 frames due to extremely poor conditions towards the end of the night. Similarly, additional photometry was also obtained using the same telescope on the night of 2020 February 3, but a combination of poor atmospheric conditions (with seeing reaching 6.5 arcsec)

and load shedding (scheduled electrical power shutdowns) at SAAO caused data gaps and fluctuations in the light curve of the order of the size of the transit signal, and so we omit these data from our analysis.

Load shedding also tainted the observations for NGTS-18 in 2019 March, resulting in a noticeable in-transit data gap of about 20 min in the final light curve. Despite being able to identify transit egress in these data, we omitted it from our final modelling process, as the data quality was too poor to obtain a reliable fit. However, we include the light curve in Fig. 1(d). We instead utilize follow-up photometry from the Lesedi telescope, taken on the nights of 2020 June 24 and 30 in the *I* and *V* bands, respectively. The *I*-band data consist of 426×15 s exposures; although it also includes a data gap of about 14 min long, this time due to an autoguider failure, the in-transit data are stable, and we thus include it in the modelling. Fortunately, the final data set in the *V* band was taken continuously over 2.29 h, and consists of 550×15 s exposures.

NGTS-16 and NGTS-17 were both observed using only the 1.0-m telescope at SAAO. For NGTS-16, we obtained two follow-up light curves on the night of 2018 December 21 (200×60 s exposures) and the night of 2019 December 5 (540×30 s exposures), while NGTS-17 was observed once on the night of 2019 February 5 (1104×15 s exposures).

A full summary of the photometric observations for each object is detailed in Table 2.

Each light curve was bias and flat-field corrected using the local PYTHON-based SAAO SHOC pipeline, which uses IRAF photometry tasks (PYRAF) and facilitates the extraction of raw and differential light curves. We used the Starlink package AUTOPHOTOM to perform aperture photometry on both our target and comparison stars, and chose apertures that gave the maximum signal-to-noise ratio. Background apertures were adjusted to account for changes in apparent star size over the night as the atmospheric conditions varied. Finally, the measured fluxes of the comparison stars for each object were used for differential photometry of our targets.

The SAAO light curves of each candidate are shown in Fig. 1. For NGTS-15 and NGTS-16, which each has two SAAO detections from the 1.0-m telescope, the data have been phase folded on the best-fitting period.

We detected a clear egress for NGTS-15 in 2018 November, as well as an ingress in 2019 December. Although seeing reached 6.4 arcsec near the beginning of the 2018 observations, resulting in large in-transit scatter for this light curve, our fitting procedure reveals that the transit depth is consistent with the NGTS data to within errors. Additionally, we note that these errors are likely underestimated for the weather-affected parts of the SAAO light curve.

Analysis of the 2018 December data for NGTS-16 revealed the majority of a transit, just missing ingress, while the 2019 December data are primarily out of transit with a few data points in egress. As with the 2018 data for NGTS-15, the 2018 data for NGTS-16 were affected by varying atmospheric conditions, with the full moon and high cloud causing in-transit scatter. However, again the transit depths between telescopes are in agreement.

Similar to the 2018 light curve for NGTS-16, we detected close to a full transit for NGTS-17, again just missing ingress. Finally, the data for NGTS-18 from the Lesedi telescope contained an egress on the night of 2020 June 24 and a full transit, including some points in egress, from the night of 2020 June 30.

For all four objects, the transits observed with SAAO were consistent with planetary companions. Subsequently, each was flagged for spectroscopic follow-up to enable mass determination.

2.3 Spectroscopic follow-up

In order to constrain the masses of the planetary companions, we obtained multi-epoch spectroscopy for radial velocity measurements. Three different fibre-fed Échelle spectrographs were used, all located at the La Silla Observatory in Chile. The HARPS spectrograph (Mayor et al. 2003) is mounted on the ESO 3.6-m telescope, CORALIE (Queloz et al. 2001a) on the Swiss 1.2-m Leonard Euler telescope, and FEROS (Kaufer & Pasquini 1998) on the 2.2-m MPG/ESO telescope. The spectrographs have a range of spectral resolutions of $R = 115\,000$, $60\,000$, and $48\,000$, respectively. Due to the faintness of the targets ($14.3 < V < 14.6$; see Tables 5, 6, 7, and 8), all HARPS spectra were collected with the high-efficiency fibre link (EGGS), which uses a fibre size of $1.4''$ instead of the usual $1.0''$ mode. The HARPS-EGGS mode trades spectral resolution for approximately twice the photon count, depending on seeing. We used the second HARPS-EGGS fibre to monitor the sky simultaneously with science observations. All four objects were observed by FEROS and at least one other spectrograph, and we obtained a minimum of 12 data points for each (see Table 3 for details; see Tables A1 and A2 for a complete list of radial velocity data for each object).

The HARPS data were reduced via the offline data reduction pipeline (DRS) before being cross-correlated with a binary G2 mask to extract radial velocities (Baranne et al. 1996). This procedure was also employed for the CORALIE data, for which the spectra were reduced using the standard CORALIE DRS. For the data collected with FEROS, the CERES reduction pipeline (Brahm, Jordán & Espinoza 2017) performed a radial velocity extraction by the same method.

Two HARPS spectra of NGTS-18 obtained on BJD 2458916.780 and 2458918.843 were contaminated by moon light. We corrected the radial velocity measurements by subtracting the signal of the simultaneous sky-fibre from the science fibre in cross-correlation function (CCF) space. The radial velocities are then extracted as per usual on the star-sky CCF. Additionally, the CORALIE radial velocities for NGTS-17 were computed while excluding the first 30 spectral orders, in which the signal-to-noise ratio was < 1 . Phase-folded plots of the radial velocity data for all four targets are shown in Fig. 2.

For all four targets, the radial velocity measurements were consistent with a Jupiter-mass planet, with semi-amplitudes of the order of $K \sim 100 \text{ m s}^{-1}$ (see Table 9) and variations in-phase with the periods derived from the photometric data. To confirm that the signals did not arise due to cool stellar spots or a blended eclipsing binary, we checked for any correlation between the radial velocity measurements and the line bisector span of the CCF (Queloz et al. 2001b). Correspondingly, no evidence was found in the spectroscopic data that contradicted the existence of a planetary companion.

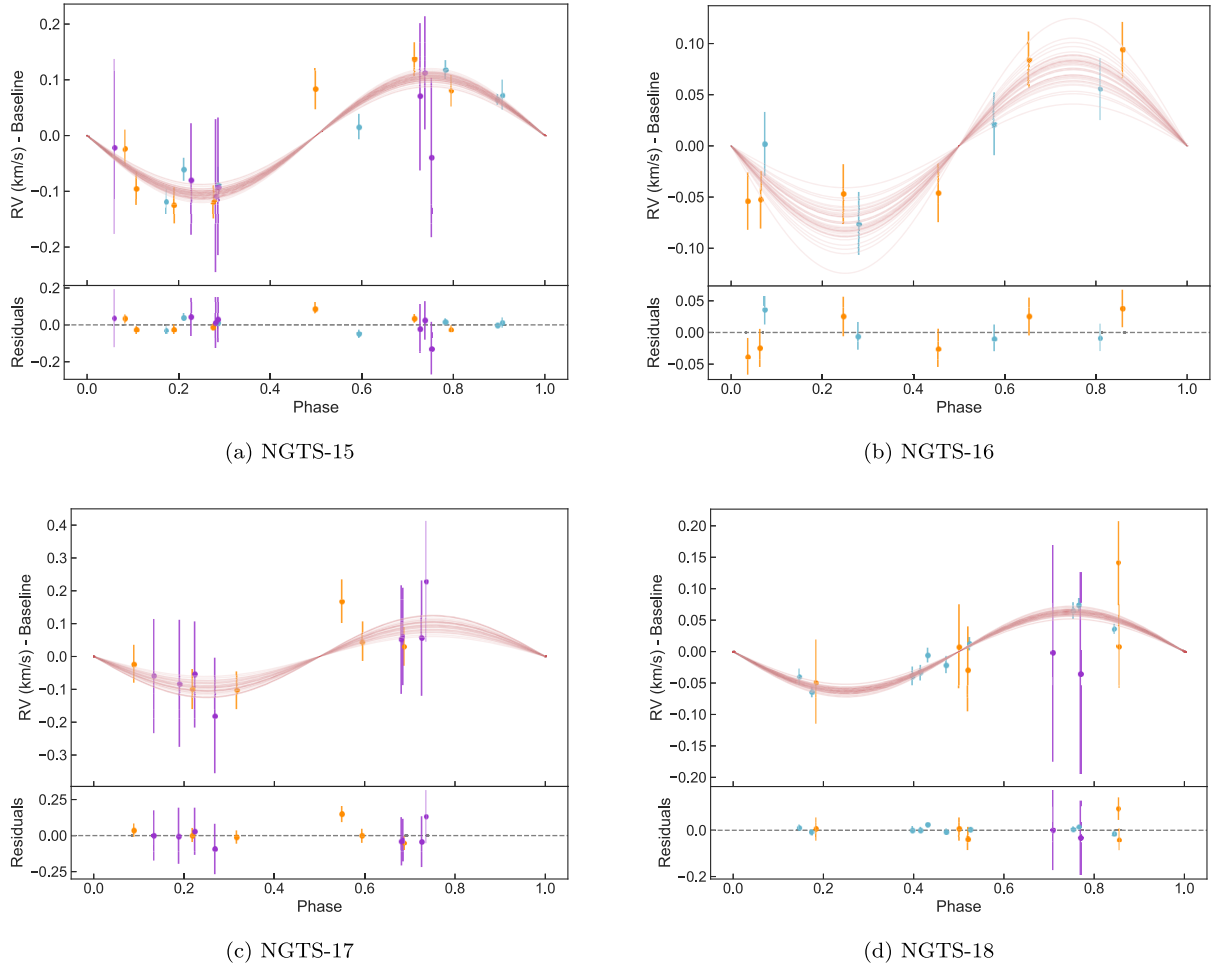
3 ANALYSIS

3.1 Stellar properties

In order to produce reliable fits to our photometric and radial velocity data for NGTS-15, NGTS-16, NGTS-17, and NGTS-18, we must first determine the stellar properties of each system. Constraining these is vital as the accuracy of the measured planetary parameters is dependent on how well we can characterize the host star. Below, we outline our stellar analysis procedure and results.

Table 3. Summary of radial velocity measurements. The full tables can be found in Appendix A.

Target	Instrument	Nights observed	n_{spectra}	Exp. time (s)	Programme	SNR _{combined}
NGTS-15	CORALIE	01/11/2018–01/03/2019	7	2700	N/A	–
	HARPS	13/09/2019–03/12/2019	7	1800	0103.C-0719(A) and 0104.C-0588(A)	16.80
	FEROS	10/09/2019–19/09/2019	7	1800	0103.A-9004(A)	–
NGTS-16	HARPS	21/01/2020–22/03/2020	6	1800	0104.C-0588(A)	21.77
	FEROS	30/12/2019–04/01/2020	6	1800	0104.A-9012(A)	–
NGTS-17	CORALIE	01/10/2019–14/02/2020	8	2700	N/A	–
	FEROS	09/11/2019–04/01/2020	12	1800	0103.A-9004(A) and 0104.A-9012(A)	59.00
NGTS-18	CORALIE	21/05/2019–14/01/2020	2	2700	N/A	–
	HARPS	02/03/2020–23/03/2020	10	2400–2700	0104.C-0588(A)	26.69
	FEROS	30/12/2019–04/01/2020	5	1800	0104.A-9012(A)	–

**Figure 2.** Phase-wrapped radial velocity measurements for all four stars from the HARPS (cyan points), FEROS (orange points), and CORALIE (purple points) spectrographs. The red lines show 20 radial velocity models generated from randomly drawn posterior samples of the ALLESFITTER fit.

3.1.1 Gaia DR2

For all four objects, we obtained additional photometric and astrometric data from *Gaia* DR2 (Gaia Collaboration 2016, 2018; see Tables 5, 6, 7, and 8). Part of these data, including the stellar radius and parallax, was utilized as priors in our SED fitting procedure (see Section 3.1.3).

The *Gaia* parallaxes, proper motions, and absolute radial velocities of each star were used to determine the Galactic velocity components

(U_{LSR} , V_{LSR} , W_{LSR}), assuming a Local Standard of Rest of $UVW = (11.1, 12.14, 7.25)$ km s^{−1} (Schönrich, Binney & Dehnen 2010). By using the selection criteria for kinematically thin disc ($V_{\text{tot}} < 50$ km s^{−1}) and kinematically thick disc ($70 < V_{\text{tot}} < 180$ km s^{−1}) objects (Gaia Collaboration 2018), we conclude that all four stars belong to the thin-disc population (see Table 4).

Finally, our host stars show no evidence of being unresolved binaries, with all four targets having an astrometric excess noise

Table 4. The galactic velocity components and total space velocities for NGTS-15–18.

Target	($U_{\text{LSR}}, V_{\text{LSR}}, W_{\text{LSR}}$)	V_{tot} (km s ^{−1})
NGTS-15	(26.875 ± 0.017, −10.106 ± 0.024, −14.065 ± 0.023)	32
NGTS-16	(23.193 ± 0.004, −1.914 ± 0.004, −15.158 ± 0.007)	28
NGTS-17	(26.073 ± 0.031, −10.465 ± 0.046, −14.478 ± 0.044)	32
NGTS-18	(9.385 ± 0.008, 7.917 ± 0.020, 9.548 ± 0.011)	16

of zero as well as a low (<0) astrometric goodness of fit in the along-scan direction (GOF_AL) in *Gaia* DR2 (Evans 2018).

3.1.2 Stellar analysis

Although we used SED fitting to derive our final stellar parameters (see Section 3.1.3), we first fit the stacked spectra for each object in order to obtain suitable priors for the key parameters with which to constrain the SED fits. For this, we used ISPEC (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019), an open-source framework for spectral analysis. ISPEC users can choose from a list of models for spectral synthesis; we employ the SPECTRUM (Gray & Corbally 1994) radiative transfer code and the solar abundance model from Asplund et al. (2009). Additionally, we use the *Gaia*-ESO Survey (GES) line list (version 5.0; Heiter et al. 2015), which covers the full wavelength range of our spectra (from 420 to 920 nm), and the MARCES.GES model atmosphere (Gustafsson et al. 2008).

We used our high-resolution HARPS data for the spectral analysis of NGTS-15, NGTS-16, and NGTS-18. Since NGTS-17 was not observed with HARPS, we instead used the FEROS spectra. For each object, we shift the spectra to the laboratory frame of reference and co-add them to produce a single, high-SNR, combined spectrum. These SNRs are reported in Table 3. We note that, although NGTS-17 has the highest SNR, the data were affected by correlated red noise, which hampered spectral analysis.

We determined the stellar effective temperature, T_{eff} , and the surface gravity, $\log g$, via fits to the $\text{H}\alpha$, Na I D , and Mg Ib lines. Individual Fe I and Fe II lines were used as diagnostics for metallicity ($[\text{Fe}/\text{H}]$) and the rotational line-of-sight broadening ($v \sin i$). Values for each parameter were obtained by synthesizing model spectra until we found an acceptable fit to the data, and uncertainties were estimated by varying the fit until the models no longer matched the stacked spectra of each object.

From our spectral analysis, we find all four stars to be metal rich, which aligns with observations that short- and intermediate-period gas giants tend to be found around more metal-rich stars than longer period gas giants (Jenkins et al. 2017; Maldonado et al. 2019).

3.1.3 SED fitting

To determine the stellar parameters of each system, we performed a fit to their SEDs. For this, we employed the PYTHON tool ARIADNE (Vines & Jenkins, in preparation), which fits catalogue photometry to different atmospheric model grids [Phoenix V2 (Husser et al. 2013), BT-Settl, BT-Cond, BT-NextGen (Hauschildt, Allard & Baron 1999; Allard, Homeier & Freytag 2012), Castelli & Kurucz (2004), Kurucz (1993)] that are then convolved with a range of filter response functions.

The SEDs were modelled by interpolating the model grids in $T_{\text{eff}}\text{--}\log g\text{--}[\text{Fe}/\text{H}]$ space, with radius, distance, and extinction in the V band used as additional model parameters. Any underestimated uncertainties in the photometry were accounted for by

including an individual excess noise term for each photometric data set.

Priors for T_{eff} , $\log g$, and $[\text{Fe}/\text{H}]$ were taken from our stellar analysis with ISPEC, while priors for the stellar radius and distance were obtained from the *Gaia* DR2 values, although we used an inflated value for the radius error to account for modelling errors. In addition, A_V was limited to the maximum line-of-sight value taken from the re-calibrated SFD galactic dust map (Schlegel, Finkbeiner & Davis 1998; Schlafly & Finkbeiner 2011). The priors for the excess noise parameters were set to a normal distribution with a mean of zero and a variance equal to five times the associated uncertainty.

The Bayesian evidence for each model was calculated using the dynesty nested sampling package, which also produces the parameters' posterior samples (Speagle 2020). The relative probabilities of the models were then used as weights with which to calculate the weighted average of each parameter via the following equation:

$$P(\theta_i) = \sum_{n=1}^N P(\theta_i | X, M_n) P(M_n | X), \quad (1)$$

where θ_i is the parameter to be averaged, $P(\theta | X, M_n)$ is the posterior distribution derived using Bayes Theorem, and $P(M_n | X)$ is the Bayesian evidence of the individual model.

Note that, by averaging over several posterior distributions, ARIADNE is able to achieve a higher precision than would typically be obtained with a single atmospheric model. Subsequently, some uncertainties may be underestimated. We therefore calculated an additional systematic error for these parameters by following the approach taken in Southworth et al. (2015), wherein each SED was fitted with the individual stellar atmosphere models before being compared to the overall Bayesian model averaging solution. By taking the largest difference between the model values and the averaged value from all posterior distributions, we were able to obtain the systematic uncertainty.

Finally, the mass value was estimated using MIST isochrones (Choi et al. 2016). The derived stellar parameters are listed in Tables 5, 6, 7, and 8. A detailed overview of the ARIADNE fitting procedure, as well as the accuracy and precision of the tool, can be found in Vines & Jenkins (in preparation).

3.2 Global modelling

We determined the physical parameters of the systems, including planet radius and mass, via a simultaneous fit to the photometric and spectroscopic data for each object. For this, we used the publicly available open-source astronomy software package ALLESFITTER (Günther & Daylan 2020, 2019), which unites the packages `ellc` (light curve and RV models; Maxted 2016), `emcee` (MCMC sampling; Foreman-Mackey et al. 2013), and `celerite` [Gaussian Process (GP) models; Foreman-Mackey et al. 2017]. The combination of these packages allows ALLESFITTER to model a variety of signals, including multistar systems, star-spots, stellar variability, and transit-timing variations.

Table 5. Stellar properties for NGTS-15. For the values from ARIADNE, we include a second systematic error from the difference between the average best-fitting value and the maximum value from the individual stellar atmosphere models.

Property	Value	Source
2MASS I.D.	04532526-3248011	2MASS
<i>Gaia</i> source I.D.	4873830691665395584	<i>Gaia</i> DR2
TIC I.D.	TIC-1333933	TIC8
Astrometric properties		
RA	04 ^h 53 ^m 25 ^s .27	<i>Gaia</i> DR2
Dec.	−32°48′01″.25	<i>Gaia</i> DR2
μ_{RA} (mas y ^{−1})	5.687 ± 0.027	<i>Gaia</i> DR2
$\mu_{\text{Dec.}}$ (mas y ^{−1})	1.316 ± 0.035	<i>Gaia</i> DR2
Parallax (mas)	1.242 ± 0.017	<i>Gaia</i> DR2
Photometric properties		
<i>V</i> (mag)	14.562 ± 0.029	APASS
<i>B</i> (mag)	15.294 ± 0.040	APASS
<i>g</i> (mag)	14.890 ± 0.034	APASS
<i>r</i> (mag)	14.341 ± 0.064	APASS
<i>i</i> (mag)	14.219 ± 0.094	APASS
<i>G</i> (mag)	14.4299 ± 0.0003	<i>Gaia</i> DR2
<i>J</i> (mag)	13.341 ± 0.030	2MASS
<i>H</i> (mag)	12.967 ± 0.035	2MASS
<i>K</i> (mag)	12.907 ± 0.036	2MASS
<i>W1</i> (mag)	12.824 ± 0.024	WISE
<i>W2</i> (mag)	12.863 ± 0.025	WISE
<i>T</i> (mag)	13.964 ± 0.006	TIC8
Derived properties		
Spectral type	G6V	ARIADNE
T_{eff} (K)	5600 ± 150	ISPEC
[Fe/H]	0.15 ± 0.1	ISPEC
$v \sin i$ (km s ^{−1})	<2	ISPEC
γ_{RV} (km s ^{−1})	34.68 ± 0.04	RV data
$\log g$	4.40 ^{+0.05} _{−0.06} ± 0.11	ARIADNE
M_s (M _⊙)	0.995 ± 0.015 ± 0.020	ARIADNE
R_s (R _⊙)	0.954 ± 0.023 ± 0.079	ARIADNE
Age (Gyr)	3.28 ^{+1.06} _{−1.38} ± 4.10	SED fitting
Distance (pc)	791 ± 19 ± 59	ARIADNE
A_v (mag)	0.025 ± 0.008 ± 0.018	ARIADNE

Note. 2MASS (Skrutskie et al. 2006); APASS (Henden & Munari 2014); WISE (Wright et al. 2010); *Gaia* (Gaia Collaboration 2016); TIC8 (Stassun et al. 2019).

Initial MCMC fits required millions of steps to converge, so we chose the nested sampling approach to produce our global fits. Our priors for transit epoch and transit depth (R_p/R_s) were refined from ORION by generating quick MCMC fits to the NGTS data using BRUCE, an open-source binary star and exoplanet analysis package.³ The results from the ARIADNE SED fits were used as priors on the stellar parameters, specifically R_s , M_s , and T_{eff} , although we used the T_{eff} error from ISPEC as this is underestimated by ARIADNE. Because all four host stars show no out-of-transit variability or trends, GP modelling was not necessary; indeed, an initial GP fit to the 2019 SAAO data of NGTS-18 incorrectly adjusted a data gap between the mid-transit and egress data points, resulting in a smaller transit depth than the true value. Furthermore, we accounted for instrumental offsets in the radial velocity data, as each object was observed with at least two different spectrographs. We adopted a quadratic limb-

Table 6. Stellar properties for NGTS-16. Systematic uncertainties are included on the values from ARIADNE as in Table 5.

Property	Value	Source
2MASS I.D.	03530331-3048164	2MASS
<i>Gaia</i> source I.D.	4886825544715697792	<i>Gaia</i> DR2
TIC I.D.	TIC-166806344	TIC8
Astrometric properties		
RA	03 ^h 53 ^m 03 ^s .34	<i>Gaia</i> DR2
Dec.	−30°48′16″.71	<i>Gaia</i> DR2
μ_{RA} (mas y ^{−1})	9.772 ± 0.031	<i>Gaia</i> DR2
$\mu_{\text{Dec.}}$ (mas y ^{−1})	−4.673 ± 0.043	<i>Gaia</i> DR2
Parallax (mas)	1.084 ± 0.021	<i>Gaia</i> DR2
Photometric properties		
<i>V</i> (mag)	14.364 ± 0.039	APASS
<i>B</i> (mag)	15.140 ± 0.006	APASS
<i>g</i> (mag)	14.743 ± 0.012	APASS
<i>r</i> (mag)	14.148 ± 0.018	APASS
<i>i</i> (mag)	13.960 ± 0.078	APASS
<i>G</i> (mag)	14.2311 ± 0.0002	<i>Gaia</i> DR2
<i>J</i> (mag)	13.090 ± 0.024	2MASS
<i>H</i> (mag)	12.735 ± 0.027	2MASS
<i>K</i> (mag)	12.647 ± 0.033	2MASS
<i>W1</i> (mag)	12.638 ± 0.025	WISE
<i>W2</i> (mag)	12.710 ± 0.025	WISE
<i>T</i> (mag)	13.743 ± 0.007	TIC8
Derived properties		
Spectral type	G7V	ARIADNE
T_{eff} (K)	5550 ± 150	ISPEC
[Fe/H]	0.35 ± 0.1	ISPEC
$v \sin i$ (km s ^{−1})	2.5 ± 0.8	ISPEC
γ_{RV} (km s ^{−1})	29.13 ± 0.01	RV data
$\log g$	4.35 ^{+0.11} _{−0.08} ± 0.14	ARIADNE
M_s (M _⊙)	1.002 ± 0.011 ± 0.029	ARIADNE
R_s (R _⊙)	1.213 ^{+0.040} _{−0.032} ± 0.102	ARIADNE
Age (Gyr)	10.29 ^{+0.74} _{−0.53} ± 1.38	SED fitting
Distance (pc)	892 ⁺²⁹ _{−23} ± 63	ARIADNE
A_v (mag)	0.013 ± 0.004 ± 0.011	ARIADNE

Note. 2MASS (Skrutskie et al. 2006); APASS (Henden & Munari 2014); WISE (Wright et al. 2010); *Gaia* (Gaia Collaboration 2016); TIC8 (Stassun et al. 2019).

darkening law as parametrized in Kipping (2013), and fit for the limb-darkening coefficients.

We ran two fits for each planet: one in which the orbital eccentricity, e , was fixed at 0, and one for which e was allowed to vary freely. Each of the latter fits resulted in non-zero values of e , at 0.102^{+0.061}_{−0.068}, 0.105^{+0.130}_{−0.079}, 0.168^{+0.093}_{−0.101}, and 0.035^{+0.033}_{−0.024} for NGTS-15b, NGTS-16b, NGTS-17b, and NGTS-18b, respectively. However, Lucy & Sweeney (1971) showed that many small values of e are spurious, and define a probabilistic test to determine whether a small e is statistically significant from 0. By adopting a 5 per cent level of significance, they find that if the condition $e > 2.45\sigma_e$ is satisfied (where σ_e is the observational uncertainty on e), then one can be confident that the measured eccentricity is real. We find that all of our measurements fail to meet this criterion, and we therefore adopt the results from the global modelling fits in which e is fixed at zero.

We use ALLESFITTER to fit our data for the key physical parameters of each system, including the planet’s orbital period P , the radius ratio R_p/R_s , and the radial velocity semi-amplitude K . Due to the large pixel scale of *TESS* (21 arcsec per pixel), the *TESS* FFI light curves for NGTS-16 and NGTS-17 contain additional faint ($G \gtrsim 17$)

³<https://github.com/samgill844/bruce>

Table 7. Stellar properties for NGTS-17. Systematic uncertainties are included on the values from ARIADNE as in Table 5.

Property	Value	Source
2MASS I.D.	04513613-3413342	2MASS
<i>Gaia</i> source I.D.	4873225513593736960	<i>Gaia</i> DR2
TIC I.D.	TIC-1309019	TIC8
Astrometric properties		
RA	04 ^h 51 ^m 36 ^s .14	<i>Gaia</i> DR2
Dec.	−34°13′34″.37	<i>Gaia</i> DR2
μ_{RA} (mas y ^{−1})	−0.190 ± 0.031	<i>Gaia</i> DR2
$\mu_{Dec.}$ (mas y ^{−1})	−11.812 ± 0.034	<i>Gaia</i> DR2
Parallax (mas)	0.932 ± 0.020	<i>Gaia</i> DR2
Photometric properties		
<i>V</i> (mag)	14.326 ± 0.030	APASS
<i>B</i> (mag)	15.043 ± 0.033	APASS
<i>g</i> (mag)	14.626 ± 0.013	APASS
<i>r</i> (mag)	14.161 ± 0.043	APASS
<i>i</i> (mag)	13.998 ± 0.081	APASS
<i>G</i> (mag)	14.2136 ± 0.0004	<i>Gaia</i> DR2
<i>J</i> (mag)	13.114 ± 0.026	2MASS
<i>H</i> (mag)	12.867 ± 0.027	2MASS
<i>K</i> (mag)	12.724 ± 0.029	2MASS
<i>W1</i> (mag)	12.739 ± 0.023	WISE
<i>W2</i> (mag)	12.747 ± 0.027	WISE
<i>T</i> (mag)	13.767 ± 0.006	TIC8
Derived properties		
Spectral type	G4V	ARIADNE
T_{eff} (K)	5650 ± 100	ISPEC
[Fe/H]	0.15 ± 0.1	ISPEC
$v \sin i$ (km s ^{−1})	4.1 ± 1.0	ISPEC
γ_{RV} (km s ^{−1})	34.81 ± 0.07	RV data
log <i>g</i>	4.00 ± 0.09 ± 0.08	ARIADNE
M_s (M _⊙)	1.025 ^{+0.015} _{−0.014} ± 0.03	ARIADNE
R_s (R _⊙)	1.337 ± 0.038 ± 0.119	ARIADNE
Age (Gyr)	9.22 ^{+0.49} _{−0.48} ± 1.32	SED fitting
Distance (pc)	1047 ⁺²⁹ _{−27} ± 108	ARIADNE
A_v (mag)	0.028 ± 0.008 ± 0.019	ARIADNE

Note. 2MASS (Skrutskie et al. 2006); APASS (Henden & Munari 2014); WISE (Wright et al. 2010); *Gaia* (Gaia Collaboration 2016); TIC8 (Stassun et al. 2019).

neighbouring stars, and we therefore fit for a small dilution in the *TESS* data. We also note some blending for NGTS-15 in the NGTS data from a singular *G* ∼ 19 mag object (identified in *Gaia* DR2), and account for this in our fitting. Note that dilution is defined in ALLESFITTER as

$$D = 1 - \frac{F_{\text{source}}}{F_{\text{source}} + F_{\text{blend}}}. \quad (2)$$

A full list of fitted properties and their values for each planet can be found in Table 9.

Fig. 1 shows the phase-folded and single light curves for the NGTS, SAAO, and *TESS* data for each object, where the red lines indicate 20 models generated from randomly drawn posterior samples of the ALLESFITTER fits. Similarly, the phase-folded radial velocity data for each star are shown in Fig. 2, with 20 generated radial velocity models.

4 INFLATION

All four planets presented in this paper have sub-Jovian masses and super-Jovian radii. Most notably, the radius of NGTS-18b is

Table 8. Stellar properties for NGTS-18. Systematic uncertainties are included on the values from ARIADNE as in Table 5.

Property	Value	Source
2MASS I.D.	12021109-3532550	2MASS
<i>Gaia</i> source I.D.	3462511310147530752	<i>Gaia</i> DR2
TIC I.D.	TIC-142211778	TIC8
Astrometric properties		
RA	12 ^h 02 ^m 11 ^s .09	<i>Gaia</i> DR2
Dec.	−35°32′54″.99	<i>Gaia</i> DR2
μ_{RA} (mas y ^{−1})	−2.416 ± 0.040	<i>Gaia</i> DR2
$\mu_{Dec.}$ (mas y ^{−1})	1.487 ± 0.025	<i>Gaia</i> DR2
Parallax (mas)	0.884 ± 0.034	<i>Gaia</i> DR2
Photometric properties		
<i>V</i> (mag)	14.540 ± 0.038	APASS
<i>B</i> (mag)	15.322 ± 0.046	APASS
<i>g</i> (mag)	14.871 ± 0.021	APASS
<i>r</i> (mag)	14.387 ± 0.080	APASS
<i>i</i> (mag)	14.189 ± 0.122	APASS
<i>G</i> (mag)	14.3896 ± 0.0003	<i>Gaia</i> DR2
<i>J</i> (mag)	13.265 ± 0.030	2MASS
<i>H</i> (mag)	12.888 ± 0.023	2MASS
<i>K</i> (mag)	12.870 ± 0.032	2MASS
<i>W1</i> (mag)	12.768 ± 0.023	WISE
<i>W2</i> (mag)	12.832 ± 0.026	WISE
<i>T</i> (mag)	13.907 ± 0.006	TIC8
Derived properties		
Spectral type	G5V	ARIADNE
T_{eff} (K)	5610 ± 150	ISPEC
[Fe/H]	0.15 ± 0.1	ISPEC
$v \sin i$ (km s ^{−1})	< 0.5	ISPEC
γ_{RV} (km s ^{−1})	5.19 ± 0.02	RV data
log <i>g</i>	4.16 ± 0.05 ± 0.05	ARIADNE
M_s (M _⊙)	1.003 ^{+0.020} _{−0.012} ± 0.022	ARIADNE
R_s (R _⊙)	1.392 ^{+0.057} _{−0.058} ± 0.201	ARIADNE
Age (Gyr)	10.84 ^{+0.40} _{−0.78} ± 1.22	SED fitting
Distance (pc)	1108 ⁺⁴⁴ _{−47} ± 158	ARIADNE
A_v (mag)	0.11 ± 0.028 ± 0.022	ARIADNE

Note. 2MASS (Skrutskie et al. 2006); APASS (Henden & Munari 2014); WISE (Wright et al. 2010); *Gaia* (Gaia Collaboration 2016); TIC8 (Stassun et al. 2019).

1.21 ± 0.18 R_J , but with a mass of only 0.409^{+0.081}_{−0.063} M_J . This is not unusual for close-in gaseous planets: The region of parameter space pertaining to low-density hot Jupiters is well populated, and is driven by inflation mechanisms that correlate with stellar irradiation (Laughlin et al. 2011; Weiss et al. 2013; Thorngren & Fortney 2018).

Studies by both Demory & Seager (2011) and Miller & Fortney (2011) suggest that these mechanisms become effective above an incident flux of ∼ 2 × 10⁵ W m^{−2}. By using the stellar luminosities and orbital parameters of each system, we calculated the irradiation received by each planet and found that all four are irradiated above this threshold (see Table 9 for values). As such, it is reasonable to expect that at least some of these planets may be affected by inflation processes and therefore exhibit radii that are larger than those predicted.

To parametrize this, we follow the procedure outlined in Costes et al. (2020), which utilizes the work of Baraffe et al. (2008) to compare planetary radii with predictions from evolutionary models, and the work of Sestovic et al. (2018) to discern the predicted additional radius change from inflation, ΔR .

Table 9. Planetary properties for each system from ALLESFITTER (see equation 2 for a definition of dilution, D).

Property	Value
(a) Planetary properties for NGTS-15b	
P (d)	$3.276\,23 \pm 0.000\,01$
T_C (BJD)	2458405.0558 ± 0.0007
T_{14} (h)	$2.504^{+0.060}_{-0.058}$
R_p/R_*	0.119 ± 0.003
a/R_*	10.00 ± 0.59
b	$0.509^{+0.086}_{-0.112}$
K (m s $^{-1}$)	106 ± 7
e	0 (fixed)
$M_p(M_J)$	$0.751^{+0.102}_{-0.088}$
$R_p(R_J)$	1.10 ± 0.10
ρ_p (g cm $^{-3}$)	$0.74^{+0.11}_{-0.10}$
a (au)	0.0441 ± 0.0046
T_{eq} (K) ^a	1146 ± 47
Irradiation (W m $^{-2}$)	$(5.78 \pm 1.33) \times 10^5$
D_{NGTS}	$0.04^{+0.01}_{-0.02}$
(b) Planetary properties for NGTS-16b	
P (d)	$4.845\,32 \pm 0.000\,02$
T_C (BJD)	2458435.6054 ± 0.0013
T_{14} (h)	$3.061^{+0.143}_{-0.136}$
R_p/R_*	0.110 ± 0.005
a/R_*	9.29 ± 0.83
b	$0.807^{+0.049}_{-0.036}$
K (m s $^{-1}$)	74^{+14}_{-12}
e	0 (fixed)
$M_p(M_J)$	$0.667^{+0.157}_{-0.129}$
$R_p(R_J)$	$1.30^{+0.13}_{-0.12}$
ρ_p (g cm $^{-3}$)	$0.38^{+0.19}_{-0.12}$
a (au)	0.0523 ± 0.0064
T_{eq} (K) ^a	1177 ± 59
Irradiation (W m $^{-2}$)	$(6.60 \pm 1.56) \times 10^5$
D_{TESS}	$0.11^{+0.03}_{-0.05}$
(c) Planetary properties for NGTS-17b	
P (d)	$3.242\,53 \pm 0.000\,01$
T_C (BJD)	2458442.5219 ± 0.0009
T_{14} (h)	$3.391^{+0.076}_{-0.073}$
R_p/R_*	0.095 ± 0.001
a/R_*	6.28 ± 0.40
b	$0.688^{+0.043}_{-0.056}$
K (m s $^{-1}$)	93^{+20}_{-17}
e	0 (fixed)
$M_p(M_J)$	$0.764^{+0.195}_{-0.164}$
$R_p(R_J)$	1.24 ± 0.11
ρ_p (g cm $^{-3}$)	$0.50^{+0.27}_{-0.17}$
a (au)	0.0391 ± 0.0043
T_{eq} (K) ^a	1457 ± 50
Irradiation (W m $^{-2}$)	$(1.58 \pm 0.34) \times 10^6$
D_{TESS}	$0.09^{+0.01}_{-0.02}$
(d) Planetary properties for NGTS-18b	
P (d)	$3.051\,25 \pm 0.000\,01$
T_C (BJD)	2458564.4506 ± 0.0007
T_{14} (h)	$3.601^{+0.055}_{-0.047}$
R_p/R_*	0.089 ± 0.001
a/R_*	6.97 ± 0.27
b	$0.183^{+0.147}_{-0.115}$
K (m s $^{-1}$)	62 ± 5

Table 9 – *continued*

Property	Value
e	0 (fixed)
$M_p(M_J)$	$0.409^{+0.081}_{-0.063}$
$R_p(R_J)$	1.21 ± 0.18
ρ_p (g cm $^{-3}$)	$0.28^{+0.25}_{-0.12}$
a (au)	0.0448 ± 0.0068
T_{eq} (K) ^a	1381^{+55}_{-53}
Irradiation (W m $^{-2}$)	$(1.15 \pm 0.37) \times 10^6$
^a $T_{eq} = T_{eff,s} \cdot \frac{(1-A)^{1/4}}{E} \cdot \sqrt{\frac{R_s}{2a}}$, where albedo $A = 0.3$ and emissivity $E = 1$.	

Baraffe et al. (2008) (hereafter B08) produced theoretical planetary evolution models that account for uncertainties in previous models, most notably quantifying the impact of heavy element enrichment. Their results include tables of predicted planetary radii that vary with the system’s physical parameters. Using these tables and adjusting for spectral type, we calculated the expected radii for all four planets and compared the result with the radii derived from our global fits. A discrepancy between the two values could indicate that inflation mechanisms have affected the radius. As B08 account for a decrease in radius with increasing heavy element mass, we assume a mass fraction of heavy material of 0.02–0.1 for each planet, which provides a realistic upper limit for the non-inflated radii.

Sestovic et al. (2018) (hereafter S18) implement hierarchical Bayesian modelling and a forward model to infer relationships between incident flux, radius, and mass using a population of 286 hot Jupiters with measured radii and masses. The resulting relations for ΔR vary according to four different mass regimes: below $0.37 M_J$, between 0.37 and $0.98 M_J$, between 0.98 and $2.50 M_J$, and over $2.50 M_J$. In this case, all four of the planets fall into the same mass range (0.37 – $0.98 M_J$), and we therefore use the corresponding equation to derive the expected radius increase due to inflation for each

$$\Delta R = 0.70 \cdot (\log_{10} F - 5.5), \quad 0.37 \leq \frac{M}{M_J} < 0.98 \quad (3)$$

(see S18 equation 11). Note that, in the S18 models, the ‘baseline’ radius, R , is set to $0.98 \pm 0.04 R_J$ for this mass regime. We therefore calculate the total expected inflated radius from the models of S18 as

$$R_{\text{Inflated}} = 0.98 + \Delta R \quad (4)$$

and compare this to the ‘true’ radii of the planets derived from global modelling.

5 DISCUSSION

We present our inflation results in Table 10, and summarize below:

NGTS-15b: Due to the poorly constrained age for this planet, the range of possible values for $R_{\text{non-inflated}}$ is so broad that it encompasses and exceeds the expected R_{inflated} values. As such, R_{observed} and its uncertainties appear consistent with both inflated and non-inflated radii, and we are therefore unable to draw firm conclusions about the nature of inflation of NGTS-15b.

NGTS-16b: R_{observed} does not agree to within uncertainties with $R_{\text{non-inflated}}$, but it is consistent with R_{inflated} . However, the discrepancy between R_{observed} and $R_{\text{non-inflated}}$ is less than 2σ , so the possibility that this planet is not inflated is also non-negligible.

Table 10. Quantifying the inflation of NGTS-15b, NGTS-16b, NGTS-17b, and NGTS-18b. R_{observed} describes the radius derived from global fits to the observational data, while $R_{\text{non-inflated}}$ and R_{inflated} describe the predicted radius from non-inflationary evolutionary models and inflationary forward models, respectively.

Target	Irradiation	Mass (M_J)	ΔR (R_J) ^a	R_{inflated} (R_J) ^a	$R_{\text{non-inflated}}$ (R_J) ^b	R_{observed} (R_J)
NGTS-15b	$(5.78 \pm 1.33) \times 10^5$	$0.751^{+0.102}_{-0.088}$	0.18 ± 0.07	1.16 ± 0.08	1.02–1.45	1.10 ± 0.10
NGTS-16b	$(6.60 \pm 1.56) \times 10^5$	$0.667^{+0.157}_{-0.129}$	0.22 ± 0.07	1.20 ± 0.08	1.01–1.07	$1.30^{+0.13}_{-0.12}$
NGTS-17b	$(1.58 \pm 0.34) \times 10^6$	$0.764^{+0.195}_{-0.164}$	0.49 ± 0.07	1.47 ± 0.08	1.01–1.08	1.24 ± 0.11
NGTS-18b	$(1.15 \pm 0.37) \times 10^6$	$0.409^{+0.081}_{-0.063}$	0.40 ± 0.10	1.38 ± 0.11	0.99–1.06	1.21 ± 0.18

^aFrom Sestovic et al. (2018).

^bFrom Baraffe et al. (2008).

NGTS-17b: We find that, while R_{observed} is higher than $R_{\text{non-inflated}}$, it is not as large as R_{inflated} . Although the discrepancy between R_{observed} and $R_{\text{non-inflated}}$ is less than 2σ , note that, due to the high irradiation of NGTS-17b, the planet exists in a region of parameter space in which S18 find that there is no evidence for a population of non-inflated hot Jupiters. It is therefore probable that this planet is inflated and that the models from S18 fail to predict the true radius value.

NGTS-18b: For this planet, the large uncertainties of R_{observed} mean that NGTS-18b can be described by both R_{inflated} and $R_{\text{non-inflated}}$; although as with NGTS-17b, we note that the large incident flux implies that this planet is likely to be inflated. In addition, we find that the lower boundary of R_{observed} falls into S18’s low-mass regime (below $0.37M_J$), and we therefore use the corresponding equation for ΔR from S18 to derive an alternative R_{inflated} value of 0.96 ± 0.9 . In this case, again R_{observed} is in agreement with R_{inflated} to within errors, but now R_{inflated} and $R_{\text{non-inflated}}$ are also entirely consistent with one another, leading us inclined to disregard this result.

Although all of the incident fluxes are larger than the typically accepted threshold for inflation ($2 \times 10^5 \text{ W m}^{-2}$) (Demory & Seager 2011; Miller & Fortney 2011), it is possible that some of these planets, particularly NGTS-15b, are not inflated. However, this boundary only describes the minimum limit at which planets begin to appear inflated, and so this result is not unexpected. In addition, S18 finds that above $\sim 10^6 \text{ W m}^{-2}$, there is no evidence for a population of non-inflated hot Jupiters in the mass range of $0.37\text{--}0.98 M_J$. The results presented here do not necessarily support this claim, but as the two planets experiencing irradiation in excess of $\sim 10^6 \text{ W m}^{-2}$ do show some evidence for inflation, we take the results from S18 as an indication that NGTS-17b and NGTS-18b are more likely to be inflated than not.

It is interesting that, based on the models of S18, we expect both NGTS-15b and NGTS-16b to possess a similarly inflated radius. While it is possible that both planets do correspond with the predicted inflated radii from S18, it is also probable that NGTS-15b is not inflated at all, especially if the system is young. However, we note that, while S18’s model successfully describes the general shape of the hot Jupiter population in the radius–flux plane (see Fig. 4), the variation in latent parameters such as heavy element fraction and system age is only accounted for in the scatter of the model; currently, the models are solely dependent on incident flux (within mass bins). We speculate that the variation in additional latent factors for the planets presented here would provide an explanation as to why two similarly irradiated planets may exhibit different levels of radius inflation. As previously mentioned, the age of NGTS-15b could reasonably lead to an uninflated radius; it is already known that hot Jupiter radii vary with age (Baraffe et al. 2008; Miller, Fortney & Jackson 2009; Thorngren & Fortney 2018), and new evidence is emerging that suggests that gaseous planets may ‘reinflate’ at late times (Hartman et al. 2016; Komacek et al. 2020; Thorngren

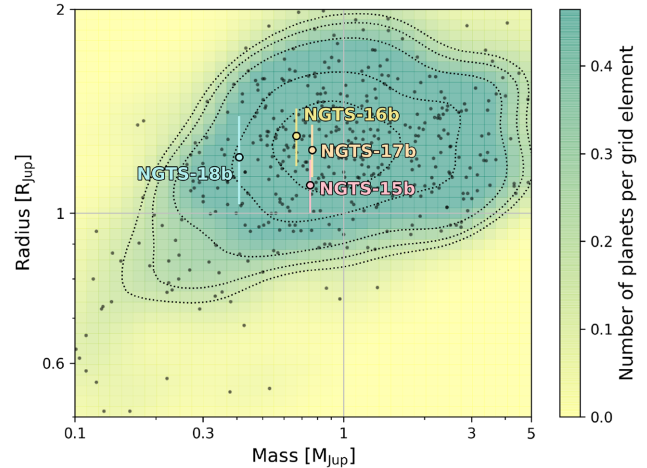


Figure 3. Exoplanets with confirmed masses and radii (grey points) from the NASA Exoplanet Archive (Akeson et al. 2013). The background and the dotted black contour lines highlight the point density per grid element of our sample. The hot Jupiters presented in this paper are plotted with error bars, and can be seen to lie comfortably within the general population of hot Jupiters. NGTS-15b to NGTS-18b are labelled with coloured circles on the plot with associated uncertainties.

et al. 2020, 2021). In addition, differing system ages could indicate a difference in planetary migration times on to short orbits, and there may have been a variation in the level of stellar irradiation since that time. This may be one explanation for the systems presented here, as the SED ages, while uncertain for the younger system, would appear to align with this. Furthermore, as noted previously, the fraction of heavy elements present in a planet will influence the radius inflation of hot Jupiters, with radii expected to decrease as Z increases (Thorngren et al. 2016, 2021).

While these parameters are described indirectly by the models of S18 as the intrinsic physical scatter in the data, the detailed effects are as-of-yet unidentified. With the number of hot Jupiter candidates increasing more than twofold since the construction of the sample from S18, it would be pertinent to update these models with a view to understanding whether the inclusion of additional hyperparameters in the Bayesian model may describe the hot Jupiter inflation relationships with greater accuracy.

Finally, despite the varying response to inflation mechanisms, we find that all four planets lie comfortably among the general population of hot Jupiters in the mass–radius plane (see Fig. 3). Additionally, all four planets again occupy a densely populated region of radius–flux parameter space (see Fig. 4).

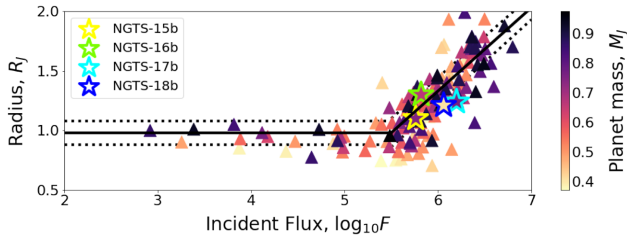


Figure 4. Exoplanets from the Exoplanet Orbit Database (Han et al. 2014) with masses between 0.37 and 0.97 M_J . We overplot the model (solid black line) from Sestovic et al. (2018) with the associated standard deviation in R (dotted black line) for hot Jupiter inflation in this mass regime. The hot Jupiters presented in this paper are plotted as stars with coloured outlines.

6 CONCLUSIONS

We report the discovery of four hot Jupiter planets: NGTS-15b, NGTS-16b, NGTS-17b, and NGTS-18b. Each planet was originally identified from photometry from the NGTS, and was confirmed through follow-up observations carried out at the SAAO with the 1.0 m and Lesedi telescopes, and radial velocity measurements made with the HARPS, CORALIE and FEROS spectrographs. Additional photometry from the *TESS* was also acquired for three of the four targets.

Global fits to these data were produced using the open-source astronomy software package ALLESFITTER (Günther & Daylan 2019, 2020), and yielded masses, radii, and orbital periods consistent with hot Jupiter planets (see Table 9). Spectral analysis via ISPEC (Blanco-Cuaresma et al. 2014; Blanco-Cuaresma 2019) and SED fitting via ARIADNE (Vines & Jenkins, in preparation) revealed the properties of the host stars in each system, which were all found to be main-sequence G-type stars (see Tables 5, 6, 7, and 8).

As part of our analysis, we noted that all four planets received a level of irradiation that surpassed the expected threshold for the onset of planetary inflation mechanisms (Demory & Seager 2011; Miller & Fortney 2011). As such, we sought to characterize any potential inflation by comparing our derived radii with predictions from evolutionary models (Baraffe et al. 2008). In addition, we examined the predicted additional radius change due to inflation, ΔR , through the flux–mass–radius relations outlined in Sestovic et al. (2018). We found that two of the planets are likely inflated when compared with non-inflationary models, and it is reasonable to assume that NGTS-18b, although consistent with both inflated and non-inflated solutions, is also inflated due to its high incident flux. We were unable to draw any firm conclusions on the nature of inflation for NGTS-15b due to the poorly constrained age for this system resulting in a broad range of non-inflated radius values. Furthermore, we note some disparity between the radii derived from global modelling and those predicted by the inflationary forward model of Sestovic et al. (2018), although all four planets were found to fit within the general hot Jupiter population (see Figs 3 and 4). We suggest that the inclusion of both new hot Jupiter data and additional hyperparameters that describe latent parameters, such as system age, into the Bayesian model may refine the relations further.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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SUPPORTING INFORMATION

Supplementary data are available at *MNRAS* online.

Table 1. NGTS photometry for each object.

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APPENDIX A: RADIAL VELOCITY DATA

Table A1. Full radial velocity data from HARPS, CORALIE and FEROS.

Target	BJD (−2450000)	RV (km s ^{−1})	RV err (km s ^{−1})	FWHM (km s ^{−1})	Contrast	BIS (km s ^{−1})	Instrument
NGTS-15	8423.852	34.764	0.102	8.204	75.167	0.421	CORALIE
	8428.738	34.574	0.100	8.117	68.305	0.013	CORALIE
	8493.712	34.632	0.157	8.681	89.838	−0.418	CORALIE
	8497.732	34.561	0.123	8.252	75.461	0.146	CORALIE
	8528.658	34.722	0.132	7.869	75.167	0.421	CORALIE
	8538.571	34.613	0.143	8.466	72.993	−1.919	CORALIE
	8543.582	34.545	0.137	8.398	60.515	0.073	CORALIE
	8736.864	34.601	0.018	10.101	0.660	−0.052	FEROS
	8739.802	34.549	0.022	6.683	30.008	0.118	HARPS
	8739.858	34.595	0.024	9.706	0.690	−0.134	FEROS
	8740.862	34.803	0.029	9.703	0.710	−0.037	FEROS
	8741.797	34.786	0.017	6.687	31.418	0.014	HARPS
	8741.833	34.799	0.018	9.685	0.680	−0.033	FEROS
	8742.782	34.696	0.024	9.440	0.690	−0.220	FEROS
	8742.863	34.625	0.019	9.705	0.670	−0.060	FEROS
	8744.850	34.856	0.021	9.769	0.670	−0.060	FEROS
	8782.766	34.581	0.031	6.959	32.833	0.013	HARPS
	8783.767	34.683	0.023	6.857	33.327	0.055	HARPS
	8784.793	34.741	0.027	6.850	33.002	0.067	HARPS
	8808.728	34.608	0.020	6.833	33.754	−0.079	HARPS
	8820.798	34.733	0.010	6.930	34.717	0.013	HARPS
NGTS-16	8847.635	29.126	0.014	9.970	0.600	0.063	FEROS
	8848.650	29.078	0.016	10.217	0.600	−0.075	FEROS
	8849.653	29.079	0.015	10.058	0.590	0.035	FEROS
	8850.616	29.209	0.014	10.002	0.600	−0.012	FEROS
	8851.619	29.219	0.014	10.034	0.600	−0.003	FEROS
	8852.614	29.072	0.015	10.112	0.600	−0.063	FEROS
	8869.629	29.155	0.009	7.650	53.996	−0.026	HARPS
	8875.604	29.190	0.009	7.697	53.738	−0.026	HARPS
	8886.579	29.136	0.011	7.693	51.044	−0.040	HARPS
	8887.572	29.058	0.010	7.649	51.040	−0.032	HARPS
	8927.511	29.148	0.009	7.625	53.670	−0.039	HARPS
	8930.509	29.090	0.030	7.605	51.292	−0.003	HARPS
NGTS-17	8737.879	34.842	0.019	10.145	0.670	−0.113	FEROS
	8739.818	34.894	0.021	10.094	0.690	−0.039	FEROS
	8741.857	34.763	0.016	9.878	0.680	0.032	FEROS
	8742.759	34.910	0.023	10.090	0.700	0.045	FEROS
	8744.784	34.768	0.024	10.102	0.690	−0.032	FEROS
	8745.853	35.032	0.039	10.180	0.700	0.138	FEROS
	8757.770	34.699	0.160	8.641	46.025	0.439	CORALIE
	8791.689	34.813	0.147	8.823	44.152	0.130	CORALIE
	8804.645	34.805	0.163	8.977	50.196	0.296	CORLAIE
	8847.672	34.801	0.017	10.239	0.660	−0.037	FEROS
	8848.674	34.702	0.017	9.955	0.660	0.051	FEROS
	8849.677	34.945	0.019	10.190	0.660	−0.024	FEROS
	8850.692	34.925	0.016	10.165	0.670	−0.016	FEROS
	8851.662	34.742	0.016	10.145	0.670	−0.019	FEROS
	8852.669	34.769	0.015	10.187	0.670	−0.030	FEROS
	8861.678	34.573	0.176	8.926	45.527	−0.231	CORALIE
	8864.664	34.672	0.191	8.971	48.217	0.255	CORALIE
	8869.639	34.809	0.174	8.683	46.440	−0.327	CORALIE
	8882.644	34.981	0.184	8.650	48.722	0.467	CORALIE
	8893.664	34.694	0.172	8.465	47.912	0.122	CORALIE

Table A2. Full radial velocity data from HARPS, CORALIE, and FEROS (cont.).

Target	BJD (−2450000)	RV (km s ^{−1})	RV err (km s ^{−1})	FWHM (km s ^{−1})	Contrast	BIS (km s ^{−1})	Instrument
NGTS-18	8624.587	5.204	0.171	8.523	54.102	−0.056	CORALIE
	8847.770	5.207	0.017	9.177	0.620	0.034	FEROS
	8848.777	5.151	0.018	9.912	0.650	0.067	FEROS
	8849.800	5.171	0.019	9.321	0.630	−0.067	FEROS
	8850.817	5.340	0.018	9.872	0.650	0.056	FEROS
	8852.793	5.207	0.016	9.746	0.650	0.053	FEROS
	8862.770	5.173	0.160	7.402	61.367	−0.494	CORALIE
	8910.839	5.182	0.010	7.556	46.878	−0.038	HARPS
	8911.815	5.206	0.009	7.510	47.123	−0.033	HARPS
	8912.822	5.106	0.008	7.510	47.168	−0.001	HARPS
	8916.780	5.150	0.013	7.438	46.887	−0.003	HARPS
	8918.843	5.130	0.014	7.557	45.336	0.048	HARPS
	8925.810	5.165	0.012	7.536	47.105	0.028	HARPS
	8926.836	5.244	0.011	7.510	46.404	−0.021	HARPS
	8928.814	5.137	0.012	7.574	46.375	−0.035	HARPS
	8929.846	5.235	0.013	7.567	46.364	0.038	HARPS
	8931.808	5.131	0.015	7.535	46.549	0.006	HARPS

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