

NGTS-33b: A Young Super-Jupiter Hosted by a Fast Rotating Massive Hot Star

Douglas R. Alves,^{1,3*} James S. Jenkins,^{2,3} Jose I. Vines,⁴ Matthew P. Battley,⁹ Monika Lendl,⁹ François Bouchy,⁹ Louise D. Nielsen,¹⁰ Samuel Gill,^{5,6} Maximiliano Moyano,⁴ D. R. Anderson,⁴ Matthew R. Burleigh,¹¹ Sarah L. Casewell,¹¹ Michael R. Goad,¹¹ Faith Hawthorn,^{5,6} Alicia Kendall,¹¹ James McCormac,^{5,6} Ares Osborn,⁸ Alexis M. S. Smith,⁷ Stéphane Udry,⁹ Peter J. Wheatley,^{5,6} Suman Saha,^{2,3} Léna Parc,⁹ Arianna Nigioni,⁹ Ioannis Apergis,^{5,6} Gavin Ramsay¹²

¹Departamento de Astronomía, Universidad de Chile, Casilla 36-D, Santiago, Chile

²Instituto de Estudios Astrofísicos, Universidad Diego Portales, Av. Ejército 441, Santiago, Chile

³Centro de Astrofísica y Tecnologías Afines (CATA), Casilla 36-D, Santiago, Chile

⁴Instituto de Astronomía, Universidad Católica del Norte, Angamos 0610, 1270709, Antofagasta, Chile

⁵Department of Physics, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL, UK

⁶Centre for Exoplanets and Habitability, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL, UK

⁷Department of Extrasolar Planets and Atmospheres, Institute of Planetary Research, German Aerospace Center (DLR), Rutherfordstraße 2, 12489 Berlin, Germany

⁸Department of Physics and Astronomy, McMaster University, 1280 Main St W, Hamilton, ON, L8S 4L8, Canada

⁹Departement d'Astronomie, Université de Genève, 51 chemin Pegasi, 1290 Sauverny, Switzerland

¹⁰University Observatory, Faculty of Physics, Ludwig-Maximilians-Universität München, Scheinerstr. 1, 81679 Munich, Germany

¹¹School of Physics and Astronomy, University of Leicester, Leicester LE1 7RH, UK

¹²Armagh Observatory and Planetarium, College Hill, Armagh, BT61 9DG, UK

ABSTRACT

In the last few decades planet search surveys have been focusing on solar type stars, and only recently the high-mass regimes. This is mostly due to challenges arising from the lack of instrumental precision, and more importantly, the inherent active nature of fast rotating massive stars. Here we report NGTS-33b (TOI-6442b), a super-Jupiter planet with mass, radius and orbital period of $3.6 \pm 0.3 M_J$, $1.64 \pm 0.07 R_J$ and 2.827972 ± 0.000001 days, respectively. The host is a fast rotating (0.6654 ± 0.0006 day) and hot ($T_{\text{eff}} = 7437 \pm 72$ K) A9V type star, with a mass and radius of $1.60 \pm 0.11 M_{\odot}$ and $1.47 \pm 0.06 R_{\odot}$, respectively. Planet structure and Gyrochronology models shows that NGTS-33 is also very young with age limits of 10-50 Myr. In addition, membership analysis points towards the star being part of the Vela OB2 association, which has an age of ~ 20 -35 Myr, thus providing further evidences about the young nature of NGTS-33. Its low bulk density of $0.19 \pm 0.03 \text{ g cm}^{-3}$ is 13% smaller than expected when compared to transiting hot Jupiters with similar masses. Such cannot be solely explained by its age, where an up to 15% inflated atmosphere is expected from planet structure models. Finally, we found that its emission spectroscopy metric is similar to JWST community targets, making the planet an interesting target for atmospheric follow-up. Therefore, NGTS-33b's discovery will not only add to the scarce population of young, massive and hot Jupiters, but will also help place further strong constraints on current formation and evolution models for such planetary systems.

Key words: techniques: photometric – techniques: radial velocities – planets and satellites: detection – planets and satellites: fundamental parameters – planets and satellites: general – stars: general.

* E-mail: douglasalvesastro12@gmail.com
dalves@das.uchile.cl

1 INTRODUCTION

The detection of the first hot Jupiters (HJ; Mayor & Queloz 1995; Charbonneau et al. 2000) set a great milestone in the exoplanet field, paving the way to the detection of several more extra-solar planets. Ground-based spectroscopic (Valenti & Fischer 2005; Jenkins et al. 2009) and photometric surveys (Bakos et al. 2004; Pollacco et al. 2006; Wheatley et al. 2013) were initially responsible for the detection and characterisation of several massive HJs. Yet, though challenging, a few Neptunes (e.g., HAT-P-11b, NGTS-14Ab; Bakos et al. 2010; Smith et al. 2021) have also been confirmed. Such selection bias towards massive planets is mostly due to the larger Doppler signal as well as transit depths induced by HJs given their mass and short orbital periods ($P < 10$ days), making their detection more favourable compared to less massive and/or longer period worlds. Besides that, ground-based missions are limited by atmospheric conditions (Cubillos et al. 2016; O’Brien et al. 2022) as well as the day-night cycle, hence challenging the discovery of long-period planets. On the other hand, space-based missions such as CoRoT (Auvergne et al. 2009), Kepler/K2 (Borucki et al. 2010) and the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015) were free of such atmospheric limitations, helping to reduce the bias by increasing the number of planet detections¹ significantly, with Kepler being responsible for the discovery of several (mini-)Neptunes ($10M_{\oplus} \leq M < 38M_{\oplus}$) and (super-)Earths ($1M_{\oplus} \leq M < 10M_{\oplus}$), whilst providing robust statistical constraints on planet occurrence rates (Mulders et al. 2015; Hsu et al. 2019), as well as the multiplicity nature of rocky worlds (Cochran et al. 2011; Gillon et al. 2017). In addition, the dearth of Neptune planets with orbital periods interior to 4 days, known as the Neptune desert, first dropped out of the Kepler data, and subsequently corroborated by the relatively low Neptune discoveries from TESS mission. Though rare, planets have been detected and characterised in this region (e.g., LTT9779b; Jenkins et al. 2020; Hoyer et al. 2023; Fernández Fernández et al. 2024), which were fundamental to constrain the most likely scenario for these planets. In addition, the evolution of giant planets may even be associated to the emergence and form of the desert, where a combination of tidal migration with atmospheric photoevaporation (Lopez & Fortney 2013; Owen & Wu 2017) may have been able to strip off the migrating giants’ envelopes, giving rise to a population of Neptune-desert planets.

Like the Neptune desert planets, the HJ population remains subjected to intense scrutiny, especially the transiting HJs (THJs), where besides their masses, radii (R_p) and bulk densities (ρ_p) can be estimated at high precision. Moreover, atmospheric follow-up may help reveal key properties (e.g. day-night temperatures, albedo/reflectivity and atmosphere abundances), making them great test beds for probing giant planet formation and evolution histories. For instance, HJs are not expected to form in-situ but farther out in the disc where an initial $\sim 10 M_{\oplus}$ protoplanet mass is fundamental to the onset of a runaway gas accretion process leading to the formation of giant planets (Pollack et al. 1996; Alibert et al. 2005; Piso & Youdin 2014). In addition, HJs formation and disc migration must occur quickly (~ 5 -10 Myr), with timescales being a function of the protostar mass as well as the disc properties, specially its mass and metallicity (see, Fortney et al. 2021). In fact, it has been noted that stellar metallicity ($[Fe/H]$) correlates with giant planet fraction (f_p), indicating that such planets are formed more effectively around metal-rich stars (Gonzalez 1997; Santos et al. 2001; Fischer & Valenti 2005; Osborn & Bayliss 2020). Moreover, an increase in

$[Fe/H]$ leads to a higher f_p , providing further evidences that disc metallicity plays an important role in the formation of giant planets (Santerne et al. 2016; Buchhave et al. 2018; Barbato et al. 2019). For instance, Jenkins et al. (2017) finds a correlation between giant hosts $[Fe/H]$ and P , where the population of giants exterior to $P \leq 100$ days are more metal-rich with a $[Fe/H]$ mean difference ~ 0.16 dex. Therefore, they point out that such correlation may indicate the initial location where giant planets formed in the protoplanetary disc. Finally, giant planets seem to be more abundant around more massive stars, where higher f_p are observed as a function of stellar mass (Johnson et al. 2010; Reffert et al. 2015; Jones et al. 2016). Such results point to a correlation between the central star and disc masses, where the former plays an important role in the type of planets that will be formed. In other words, an increase in the stellar mass leads to higher disc masses, hence more material with which to quickly form massive giant planets before the disc disperses. Therefore, these results are in agreement with the current findings of massive stars harbouring massive gas giant planets, particularly at short periods where the HJ population is located.

As mentioned, the evolution of giant planets may have been subjected to disc migration rather than in-situ formation. Further evidence against the latter include the detection of atmospheric escape in HJs (e.g., HD209458b, HD 189733b, KELT-19b; Vidal-Madjar et al. 2003; Des Etangs et al. 2010; Wyttenbach et al. 2020) and high obliquities of close-in giants, which may be explained by the planets’ evolution through high eccentricity (e) migration by secular interactions with outer companions (Fortney et al. 2021; Vick et al. 2023). In fact, a handful of hot hosts have massive HJs with non-zero obliquities (e.g., KELT-17b, MASCARA-1b, TOI-1431b), with some even retrograde (HAT-P-14b; Winn et al. 2011), whereas cool stars tend to have HJs with low obliquities (Winn et al. 2011), thus showing that massive giant planets might have gone through multiple migration channels.

Here, we report the detection of NGTS-33b, the first NGTS discovery of a super-Jupiter hosted by a massive star. This detection will add to the small, but growing number of massive systems, that will help us to better understand the formation and evolution processes of massive planets around hot stars. The manuscript is organised as follows, in § 2, we present the photometry extraction from NGTS and TESS lightcurves, spectroscopic follow-up with FEROS, HARPS and CORALIE and their respective spectral line activity diagnosis. § 3 describes the data analysis, where we extract stellar parameters (§ 3.2), assess its age (§ 3.2.1), perform a global modelling to derive the planetary parameters (§ 3.3). Stellar rotation period, transit timing variation as well as dynamical stability were probed in § 3.1, 3.4, and 3.5, respectively. Finally, we discuss our results in § 4 and set out the conclusions in § 5.

1.1 The Next Generation Transit Survey

The Next Generation Transit Survey (NGTS; Chazelas et al., 2012; McCormac et al., 2017; Wheatley et al., 2018) is located at the ESO Paranal Observatory in Chile, with the objective of detecting new transiting planetary systems. The consortium has 12 telescopes with 0.2 m diameter each, and individual fields of view of 8 deg^2 , which combined provides a wide-field of 96 deg^2 .

The NGTS detectors host $2K \times 2K$ pixels, with individual pixels measuring $13.5 \mu\text{m}$, which corresponds to an on-sky size of 5 arcseconds/pixel, thus providing high sensitivity images over a wavelength domain between 520–890nm. This combination allows 150 ppm photometry to be obtained on bright stars ($V < 10$ mags) for multi-camera observations, while for single telescope mode at

¹ 5675 planets on 15 May 2024 according to <https://exoplanet.eu/>

30 min cadence, a precision of 400 ppm is achievable (Bayliss et al. 2022). The project has been operational since February 2016, and over the past 8 years has so far acquired over 400 billion measurements of over 30 million stars. Within this treasure-trove of data, the NGTS has discovered 26 new planetary systems (e.g., Bayliss et al., 2018; Bryant et al., 2020; Tilbrook et al., 2021; Bouchy et al., 2024), with more yet to be confirmed. A few of the highlights include the discovery of the Neptune desert planet NGTS-4b (West et al. 2019), an ultra short period Jupiter NGTS-6b (Vines et al. 2019), the shortest period hot Jupiter NGTS-10b around a K5V star (McCormac et al. 2020), an inflated HJ around a low-mass and metal-poor K dwarf (Alves et al. 2022), and a few warm planets (e.g., NGTS-29b, NGTS-30b; Gill et al. 2024; Battley et al. 2024).

2 OBSERVATIONS

Here we describe the photometry and spectroscopic data acquisition and reduction that lead to the discovery of NGTS-33b. Table 1, 2, and 3 show the NGTS and TESS observation dates and settings, a portion of the normalised photometry and radial velocity (RV) used in the analysis, respectively.

2.1 NGTS Photometry

NGTS-33 observations were taken during 2019–2021 in single camera mode and with 10 seconds exposure time per frame, as summarised in Table 1. Three independent telescopes were used at different epochs, yielding a total of 309,426 images from which stellar brightness was measured by aperture photometry with the CASU-Tools² package. As part of the data reduction, an adapted version of the SysRem algorithm (Tamuz et al. 2005) and the box least-squares (BLS) fitting algorithm (Kovács et al. 2002; Collier Cameron et al. 2006) ORION were used to remove nightly trends caused by atmospheric extinction and search for periodic transits in the timeseries, respectively. 28 transits in total were detected, from which seven had complete time coverage. A strong signal was detected at 2.83 days, and a validation process began in order to either confirm the signal as a transiting hot Jupiter or reject it as a false positive detection. For example, one of the vetting tests deal with background eclipsing binaries, where consecutive transits showing odd-even and/or V shaped morphologies could indicate candidates are false positives. NGTS-33 passed every validation step, and therefore further photometry and RV follow-up were obtained. Figure 1 shows the NGTS detection lightcurve wrapped around the best-fitting period 2.827969 ± 0.000002 d computed from the global modelling (§ 3.3). For a thorough description of the NGTS mission, data reduction, and acquisition, we refer the reader to Wheatley et al. (2018).

2.2 TESS Photometry

TESS (Ricker et al. 2015) observed NGTS-33 in Sectors 07, 33, 34 and 61 with cadences of 30, 5, 5, and 3.33 minutes, respectively. The data were acquired from the Mikulski Archive for Space Telescopes (MAST), using the `lightkurve` package (Lightkurve Collaboration et al. 2018). The first three sectors were available through distinct data reduction teams, to name a few, the Science Processing Operations Center (TESS-SPOC; Jenkins et al. 2016;

Table 1. NGTS and TESS observation settings

| Start date | | NGTS Mission | nights | Camera |
|-------------|-------------|--------------|--------|--------|
| End date | | | | |
| 2019-Dec-18 | 2020-Mar-21 | | 94 | 803 |
| 2020-Sep-28 | 2021-Mar-25 | | 178 | 804 |
| 2021-Apr-26 | 2021-Jun-12 | | 47 | 809 |
| Start date | | TESS Mission | Sector | Camera |
| End date | | | | |
| 2019-Jan-07 | 2019-Feb-02 | | 07 | 03 |
| 2020-Dec-17 | 2021-Jan-13 | | 33 | 03 |
| 2021-Jan-13 | 2021-Feb-09 | | 34 | 03 |
| 2023-Jan-18 | 2023-Feb-12 | | 61 | 03 |

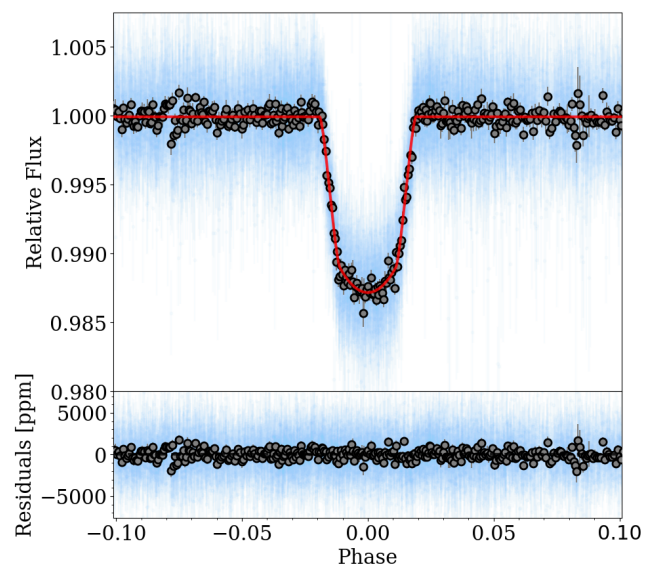


Figure 1. **Top:** NGTS detrended lightcurve phase-folded to the best-fitting period listed in Table 5 and zoomed to show the transit event. Blue and black circles correspond to modelled photometric data and binned data with the associated photon noise error. The red line and shaded region show the median transit model and its $1-\sigma$ confidence interval. **Bottom:** residuals to the best fit model.

Caldwell et al. 2020), the Quick Look Pipeline (QLP; Kunimoto et al. 2021), and the Cluster Difference Imaging Photometric Survey (CDIPS; Bouma et al. 2019), with the later providing further evidences on the young nature of NGTS-33 (see § 3.2.1). Sector 61 is thus far only available through the QLP pipeline, thus upon analysis of the data we opted to use TESS-SPOC lightcurves for Sectors 07, 33, and 34 as the data showed slightly less out of transit dispersion. Fig. 2 shows the detrended phase-folded lightcurve as well as the best-fitting transit model derived in § 3.3.

Lastly, we point out that the planet was independently detected by NGTS, despite TESS first observed the star in January 2019 with the release of sector 07. The 30-minute cadence photometry did not provide sufficient evidence for a planet candidate at that time, with a TOI alert issued nearly four years later, on May 3, 2023, by which point NGTS had already gathered evidence for a confirmed planet. NGTS monitoring spanned from March 2019 to June 2021, during which multiple transit events were detected prior to the release of TESS sector 33 in December 2020. Finally, our radial velocity follow-up began on April 14, 2022, and continued

² <http://casu.ast.cam.ac.uk/surveys-projects/software-release>

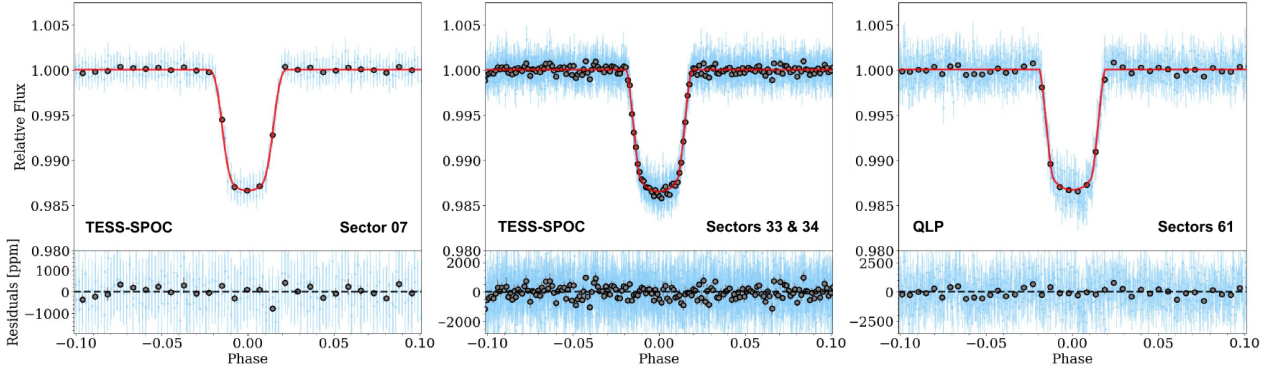


Figure 2. **Left:** Phase-folded, 30-minute detrended lightcurve from TESS-SPOC, Sector 07. **Center:** The same as the left plot but for Sectors 34 and 35 at 5-minute cadences. **Right:** Phase-folded, 3.33-minute detrended light curve from QLP, Sector 61. Colours and labels correspond to Fig. 1

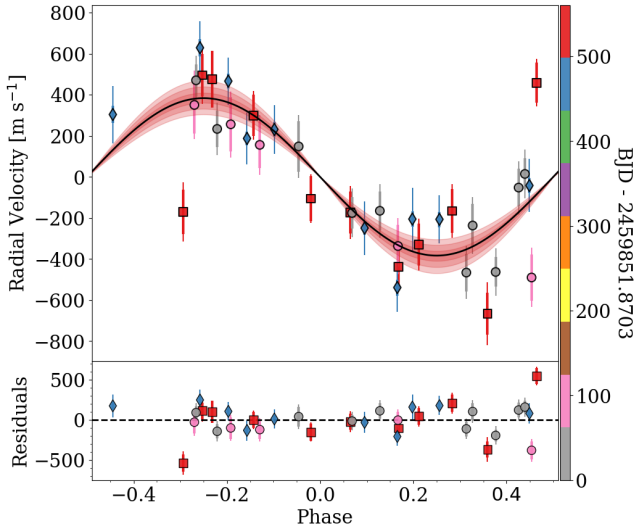


Figure 3. **Top:** RV phase-folded to the best-fitting period listed in Table 5. RV data is colour-coded in time with the black line and light red shaded region showing the median transit model and its 1, 2 and 3- σ confidence intervals. FEROS, HARPS and CORALIE RVs are highlighted by the circles, diamonds and squares, respectively. **Bottom:** residuals to the best fit model.

until April 12, 2024, with NGTS-33b being labelled as TOI-6442 during this period.

2.3 Spectroscopic Follow Up

2.3.1 FEROS

19 high-resolution echelle spectra were obtained for NGTS-33 during UT 2022-04-14 through 2023-01-16 under the FEROS program ID 0110.A-9035(A) (PI: JIV) on the MPG/ESO 2.2-m (Kaufer et al. 1999) telescope at the La Silla Observatory in Chile. The 500-1200 sec exposure times spectra were reduced using the automated CERES pipeline (Brahm et al. 2017), which performs all the steps in the CCF reduction, optimally extracts the spectra and performs wavelength calibration, corrects for instrumental drift, and normalises the continuum. CERES computes RVs using the cross-correlation function (CCF) method using a G2 mask. Additionally, we obtain the bisector velocity spans (BIS) which track stellar activity, with any

Table 2. NGTS and TESS photometry for NGTS-33. The full Table is available in a machine-readable format from the online journal. A portion is shown here for guidance.

| Time (BJD _{TDB} -2457000) | Flux (normalised) | Flux error | Instrument |
|---------------------------------------|----------------------|---------------|------------|
| ... | ... | ... | ... |
| 1491.65978 | 1.0004 | 0.0005 | TESS |
| 1491.68061 | 1.0003 | 0.0005 | TESS |
| 1491.70144 | 0.9995 | 0.0005 | TESS |
| 1491.72228 | 0.9991 | 0.0005 | TESS |
| 1491.74311 | 0.9991 | 0.0005 | TESS |
| ... | ... | ... | ... |
| 1836.59516 | 0.9964 | 0.0019 | NGTS |
| 1836.59658 | 1.0012 | 0.0032 | NGTS |
| 1836.59792 | 0.9944 | 0.0029 | NGTS |
| 1836.59933 | 0.9969 | 0.0014 | NGTS |
| 1836.60074 | 0.9972 | 0.0023 | NGTS |
| ... | ... | ... | ... |
| 2201.74242 | 0.9983 | 0.0009 | TESS |
| 2201.74936 | 0.9988 | 0.0009 | TESS |
| 2201.75631 | 0.9992 | 0.0009 | TESS |
| 2201.76325 | 1.0011 | 0.0009 | TESS |
| 2201.77020 | 1.0015 | 0.0009 | TESS |
| ... | ... | ... | ... |
| 2229.04839 | 0.9985 | 0.0009 | TESS |
| 2229.05534 | 0.9997 | 0.0009 | TESS |
| 2229.06228 | 1.0003 | 0.0000 | TESS |
| 2229.06923 | 1.0005 | 0.0009 | TESS |
| ... | ... | ... | ... |
| 2962.80386 | 0.9977 | 0.0006 | TESS |
| 2962.80849 | 1.0031 | 0.0018 | TESS |
| 2962.81544 | 0.9989 | 0.0008 | TESS |
| 2962.82238 | 0.9995 | 0.0025 | TESS |
| 2962.82933 | 1.0002 | 0.0012 | TESS |

correlation between the BIS and the RVs providing evidence for instrumental, and/or stellar effects impacting the observed spectra. Finally, upon inspection of the reduced data, we dropped the first 4 RVs given their low SNRs and performed the global model in § 3.3 with 15 FEROS RVs.

2.3.2 HARPS

We obtained 10 high-resolution echelle spectra for NGTS-33 during UT 2024-01-06 through 2024-01-10 under the HARPS program

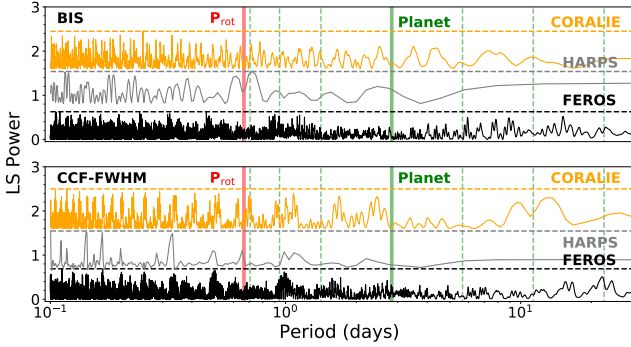


Figure 4. Periodogram of the line Bisectors (top panel) and CCF-FWHM (bottom panel) for FEROS (in black), HARPS (in gray) and CORALIE (in yellow). The false alarm probability level at the highest peak are shown as horizontal black, gray and yellow lines for FEROS, HARPS, and CORALIE, respectively. The BIS and CCF-FWHM FAPs at highest peaks for FEROS, HARPS, and CORALIE are 0.06, 0.59, 0.05 and 0.04, 0.01, 0.02, respectively. The planet’s orbital period is highlighted by the green vertical line with dashed lines showing the alias 1/8, 1/4, 1/2, 2,3 and 4 from left to right, respectively, and the stellar rotation marked by the red vertical line

ID 112.25QD (PI: DRA) on the ESO 3.6 m (Mayor et al. 2003) telescope at the La Silla Observatory in Chile. The high accuracy mode (HAM) was used, where we achieved a typical signal-to-noise (SNR) of 35 per pixel at 6500 Å and an RV precision of $\sim 37 \text{ m s}^{-1}$ with exposure times of 1800–2100 seconds depending on weather and seeing conditions. The RV measurements were computed with the standard HARPS pipeline (Lovis & Pepe 2007) using the following binary masks for the cross-correlation: G2, K5, K0, and M4, where agreement was found amongst the RVs estimated with these binary masks. Given that NGTS-33 is an F-type star, we adopted the RVs measured from the cross-correlation with a G2 binary mask as it is the closest in spectral type to our target.

2.3.3 CORALIE

The Swiss 1.2m (Queloz et al. 2000) at the La Silla observatory has been used to collect 11 high-resolution spectra with the CORALIE spectrograph. It has two fibers, with one centred on the target while the other directed to either the sky or the Fabry-Pérot (FP) etalon for purposes of background subtraction or simultaneous drift calibration, respectively. Our observations made use of the FP mode, where a spectral resolution of $\sim 60,000$ and wavelength coverage of 390–680 nm allowed us to achieve a typical RV precision of $\sim 100 \text{ m s}^{-1}$ during the data acquisition on 2024 February 27 through 2024 April 12 with 30 min exposure times. The spectra was reduced by the standard CORALIE pipeline, and RVs determined through the cross-correlation method with a binary G2 mask (Pepe et al. 2002). Further line diagnosis (e.g., FWHM-CCF and BIS) were also extracted during the data reduction.

2.3.4 Spectral diagnosis

Radial velocities rely on the accurate measurement of spectral line centroids. However, stellar activity could affect spectral line profiles, producing spurious periodic RV patterns that could mimic a planetary signal. Diagnosis of spectral lines are a common approach that provides further confidence on the planetary nature of the signal,

Table 3. NGTS-33 follow-up Radial Velocities from FEROS, HARPS and CORALIE

| BJD _{TDB} | RV (m s^{-1}) | RV err (m s^{-1}) | INSTRUMENT (m s^{-1}) |
|--------------------|-----------------------------|---------------------------------|-------------------------------------|
| -2457000 | | | |
| 2852.87014602 | 19351.7 | 89.7 | FEROS |
| 2853.85667801 | 18666.5 | 94.2 | FEROS |
| ... | ... | ... | ... |
| 3317.55154657 | 18602.2 | 32.4 | HARPS |
| 3318.55134786 | 18553.0 | 36.6 | HARPS |
| ... | ... | ... | ... |
| 3396.64685773 | 18466.2 | 101.3 | CORALIE |
| 3398.57967810 | 19397.1 | 102.4 | CORALIE |

where correlation between the RVs with parameters such as activity indexes, line bisectors (BIS) or their full width at half maxima (FWHM) are a proxy for activity induced RV variation, rather than a planetary nature. Therefore, we estimate the correlation between RVs against BIS and FWHM-CCF with the Pearson coefficient in Eq. 1,

$$r = \frac{\sum(RV_i - \bar{RV})(x_i - \bar{x})}{\sqrt{\sum(RV_i - \bar{RV})^2 \sum(x_i - \bar{x})^2}} \quad (1)$$

where x_i and \bar{x} represents the individual data points and their mean value for either BIS or FWHM. The r coefficient between the RVs and BIS for FEROS, HARPS, and CORALIE are 0.193, 0.081, and 0.32, respectively, while for the FWHM-CCF for FEROS, HARPS, and CORALIE, the r values are 0.02, 0.04, and -0.26, respectively. The Pearson r coefficient limits are -1 to 1, with values close to zero indicating that little correlation is present in the datasets. Finally, Figure 4 shows the LS periodogram for BIS and FWHM computed from FEROS, HARPS and CORALIE data, an offset was applied for better visualisation. The false alarm probability (FAP) at the respective instrument highest periodogram peaks are marked as horizontal dashed lines, with no significant peak present at the orbital period of NGTS-33b.

Lastly, the Gaia DR3 catalogue was examined around NGTS-33 to exclude potential contamination from a background eclipsing binary. This search identified five neighbouring stars within the 21-arcsecond TESS pixel, each with G magnitudes between 6.4 and 9.2 fainter than NGTS-33, and renormalised unit weight error (RUWE) values below 1.3. Although high-spatial-resolution imaging is unavailable, the NGTS pixel scale is four times finer than TESS, meaning that only one of these stars falls within the NGTS pixel. This star, named GAIA DR3 5590415817155700480, lies 3.1 arcseconds from NGTS-33 and has a G-band magnitude of 20, thus contributing negligible flux in the aperture. Its distance also places it outside the 1" HARPS fibre. Additionally, the HARPS CCFs were inspected and show no evidence of wings or secondary dips typically seen in spectroscopic binaries, thus given our dataset, it is unlikely that NGTS-33 is part of a binary systems.

3 DATA ANALYSIS

3.1 Stellar Rotation Analysis

The star’s magnetic fields can prevent local convective motion in the photosphere, consequently blocking the radial heat transfer, thus leading to the appearance of darker and cooler spots compared to the surroundings. Such regions are associated to stellar spots, and

are known to be more frequent with increasing stellar activity. As the star spins, its motion brings these spots in and out of sight, causing a periodic brightness variability in the photometric time-series. Therefore, the measurement of the stellar rotation is possible assuming the spot motions are solely due to the stellar spin.

Following the procedures laid out in previous NGTS rotation works (Gillen et al. 2020; Smith et al. 2023), we derived NGTS-33 rotation period with the Lomb-Scargle (LS; VanderPlas 2018) and the Auto-Correlation Function (ACF; Kreutzer et al. 2023) methods. Both methods rely on distinct assumptions, thus having advantages and limitations. The LS method assumes a sinusoidal function to model the rotation signal, mostly suited for stars that present steady photometric variability, with spot timescales larger than the rotation period. On the other hand, the ACF technique is a more flexible and model-free technique, which measures the degree of similarity between different parts of the dataset (see, McQuillan et al. 2014; Gillen et al. 2020). To derive the best-fitting period from the ACF we used the undamped simple harmonic oscillator (uSHO) described in Eq 2, with τ defining the decay timescale, A and B to adjust for the ACF power, and y_0 to adjust for the offset.

$$y(t) = e^{-\frac{t}{\tau}} \left(A \cos \frac{2\pi t}{P_{\text{rot}}} + B \cos \frac{4\pi t}{P_{\text{rot}}} \right) + y_0 \quad (2)$$

Prior to the period search, we masked the transits, binned the data to 30 minute cadences and median normalised it. Fig 5 shows the LS periodogram and the ACF model in the top panel left. The green and blue vertical bars shows that both methods agree to the same 0.67d periodic signal. The top right panel shows the folded lightcurve to the LS period at maximum power. We estimated a $P_{\text{rot}}^{\text{TESS}} = 0.6654 \pm 0.0006$ and $A_{\text{rot}}^{\text{TESS}} = 1.21 \pm 0.02$ ppt from LS periodograms with uncertainties from bootstrapping with 10,000 iterations. For the NGTS photometry, the LS periodogram showed the 1-day peak as the main signal, which is commonly associated with the day-night cycles in ground-based missions. Upon removing it by applying a Savitzky–Golay filter, we did the same procedures described above to probe for rotation signatures. Fig 5 in the left panel shows the cleaned NGTS data periodogram, where the rotation peak of 0.66 day is present, and followed by its 3rd harmonic marked in vertical dashed lines. The rotation period and amplitude estimated from NGTS photometry is $P_{\text{rot}}^{\text{NGTS}} = 0.665 \pm 0.001$ and $A_{\text{rot}}^{\text{NGTS}} = 1.66 \pm 0.08$ ppt, with uncertainties estimated from bootstrapping with 10,000 iterations. The ACF applied to NGTS did not converge due to the several gaps inherent in ground-based missions. The rotation periods from both instruments are in statistical agreement, while the NGTS amplitude is $\sim 6\text{-}\sigma$ away from that measured by TESS. Such amplitude mismatch between TESS and NGTS is likely due to spot evolution between measurements from NGTS and TESS, though the instruments distinct photometric band-passes might have also played a role as spots contrast vary with wavelengths or a combination of both.

As TESS data is comprised of 3 distinct sectors, we repeated the analysis above on a per-sector basis. Although we recover the same 0.67 days signal, a second signal at ~ 0.8 days is present and dominant in sector 7, yet with a LS power difference of $\sim 1\%$. Yet, for sectors 33 and 34, the 0.67 days signal becomes more significant with a power difference of $\sim 7\%$ and $\sim 10\%$, respectively, thus why the rotation from the joint lightcurve favoured the 0.67 days period. In addition, the periods derived from ACF for sectors 7, 33, 34 are 0.8, 0.66, and 0.67 days, respectively, thus confirming the LS peaks. We have also carried out the same analysis for QLP lightcurves, and reached the same periods preferences from LS and ACF methods, thus implying that the results are pipeline independent and likely

astrophysical. The LS periodogram on the QLP sector 61 showed the 0.8 and 0.67 days periods at similar power, whereas the ACF period was 0.66 days. The NGTS periodogram shows the 0.67 d peak and its harmonics at a much larger power (Fig. 5 bottom) compared to the 0.8 day, which after subtracting the 0.67 d, it becomes apparent, with a measured A_{rot} of 0.90 ± 0.11 , and power difference between the periods of $\sim 13\%$, thus weaker than the main 0.67d signal. Although both 0.67 and 0.8 days signals are significant in the per-sector TESS analysis, we adopted the 0.67 days as it is (1) the dominant signal from the analysis in the joint lightcurve from both LS and ACF methods, (2) it is also the dominant peak in the NGTS data, and (3) its larger amplitude signal compared to the 0.8 d amplitude in TESS (0.63 ± 0.03 ppt) and NGTS (0.90 ± 0.11 ppt). Nonetheless, the 0.67 and 0.8 day signals are likely astrophysical as they are present in both instruments. It is possible that due to the nature of fast rotators, spots could have been propelled towards higher latitudes through the coriolis force. As spots typical lifetimes are of a few days to months, it may be possible that TESS captured distinct spot distributions over sector 7 where the 0.8 day dominates, and the two consecutive sectors 33 and 34, with dominance on the 0.67 d signal. In order to rule out that any of the signals has its origin on UCAC4 271-014742, the nearby star labeled as number 2 in Fig 7, we repeat the rotation analysis for this star using the uncontaminated NGTS photometric time-series. We confirm the rotation period of ~ 0.11 d from GAIA, and derive an amplitude of $A = 7.26 \pm 0.26$ ppt as shown in Figure A3. As the 0.67d and 0.8d are not present in the LS periodogram, with the ACF method is agreement with the LS period at maximum power, we conclude that both 0.67 and 0.8 days signals are likely originated from NGTS-33 rather than UCAC4 271-014742.

We investigated the possibility that the lightcurve periodicity are related to pulsations rather than rotation. NGTS-33 stellar properties place it just outside the bottom of the instability strip near the class of γ Doradus. Such stars are late A to early F spectral types, with masses between 1.4 and 2.0 M_{\odot} , and multi-periodic g-mode induced variability with amplitudes no larger than 0.1 mag and periods of the order of 1 day. Although we do not completely rule out the pulsating nature of these signals, spot-crossing events observed in TESS provide robust evidence for the rotation nature of the photometric periodicity. Fig. A2 shows these events, with the first two transits from top to bottom displaying features consistent with spot-crossing, while the last transit, we interpret as a spot entering the line-of-sight, thus reducing the flux. Moreover, spot evolution could well explain the power variability of the 0.67 and 0.8 day signals due to distinct spot distributions as a function time. Additionally, line blending due to rotational broadening evidenced by the lack of Li as well as Fe lines to trace the host age and the projected velocity ($v \sin i_*$), respectively, provides further evidence that the photometric variability are indeed from a spot modulated time-series. Finally, an estimated value of $v \sin i_* \sim 111.87 \text{ km s}^{-1}$ was computed from the star's radius and adopted rotation period from Table 4. A measurement of $v \sin i_*$ was not possible due to a combination of low SNR, e.g., HARPS SNR 28-35, and line blending. However, even though spectral lines are affected by several physical mechanisms (e.g., collisional broadening) depending on wavelength and stellar properties (e.g., $\log g$, T_{eff}), the CCF shape provides a rough estimate of the averaged spectral line profile, from which we computed the HARPS FWHM-CCF to be $\sim 35\text{-}38 \text{ km/s}$. Rewriting the $v \sin i_*$ relation as $i_* = \arcsin \frac{v \sin i_*}{2 \times \pi R_S / P_{\text{rot}}}$ (see e.g., Hirano et al. 2014), and using the FWHM-CCF as proxy for $v \sin i_*$, we computed i_* to be about 18-20 degrees. This inclination is in

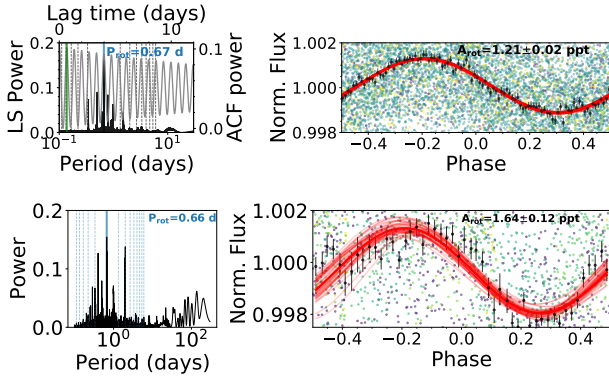


Figure 5. Top: The left panel shows the SPOC-TESS LS periodogram in black and ACF in gray, with the bottom and left axes representing the LS periodogram, while the top and left axes are for the ACF model. The vertical blue and green bars corresponding to the optimal periods from LS and ACF, respectively. The blue coloured P_{rot} at the top right shows both the period at maximum power of the LS periodogram and the period from the ACF. The right panel shows the TESS data folded to the LS best-fitting period colour-coded by time evolving from yellow to purple. Black points are binned in phase domain, with a sinusoidal model and 50 realisations drawn from the final distribution shown in red. A_{rot} shows the median and $1-\sigma$ best-fitting model.

Bottom: The same as described in the top panel for NGTS data. The ACF is not shown as it did not converged likely due to the gaps in the NGTS data.

agreement to (Dong & Foreman-Mackey 2023), which found that $72 \pm 9\%$ of the systems with measured sky-projected stellar obliquities have values less than 40 degrees. We point out that a more complete obliquity analysis will be presented in a follow-up paper where the Rossiter-McLaughlin for NGTS-33 will be investigated.

3.2 Stellar Properties

NGTS-33 parameters were estimated using the publicly available ARIADNE python package (Vines & Jenkins 2022). The code is based on the spectral energy distribution (SED) fitting method, which consists of fitting archival photometry to synthetic magnitudes from interpolated grids of stellar atmosphere models. The synthetic photometry is computed from convolving a given model with several filter response functions (see available SED models in Vines & Jenkins 2022) and scaled by $(R_s/D)^2$, with D being the star’s distance to the sun. An excess noise term is introduced for each photometric measurement in order to account for underestimated uncertainties. Finally, a cost function with input parameters T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$, and V band extinction (A_V) are minimised with (DYNESTY; Speagle 2020), a nested sampling algorithm used to effectively search the parameter space, and find the best set of synthetic fluxes from a given SED model with stellar properties that best matches the observed photometry.

ARIADNE performs the above steps for several atmosphere libraries, to name a few, Phoenix V2 (Husser et al. 2013), BT-Settl (Hauschildt et al. 1999; Allard et al. 2012), Castelli & Kurucz (2004), and Kurucz KURUCZ (1993). The code will output stellar posterior distributions from fits using each library, where the adopted stellar parameters are derived from the averaged posterior distributions weighted by their respective Bayesian evidences. Such a Bayesian averaging method helps to mitigate the assumptions and limitations from individual stellar atmosphere model, thus

yielding precise stellar parameters, particularly the R_s and T_{eff} , which are key to inform the global modelling of NGTS-33b (see § 3.3). Finally, T_{eff} , $\log g$, $[\text{Fe}/\text{H}]$ as well as additional quantities such as D , R_s , and A_V from ARIADNE are used to automatically derive the stellar age (t_s), M_s , and the equal evolutionary points from the isochrone package (Morton 2015).

We set up ARIADNE with priors defined in Table A1, where $\mathcal{N}(\mu, \sigma^2)$ and $\mathcal{U}(a, b)$ define normal and uniform priors with μ , σ^2 , a , and b representing the median, variance, and lower and upper limits, respectively. We opted for priors somewhat centred around NGTS-33 GAIA DR3³ parameters as preliminary tests with broad and uninformative priors were consistent with the values reported by GAIA, which are: $T_{\text{eff}} = 7213 \pm 9 \text{ K}$, $\log g = 4.19^{+0.03}_{-0.01} \text{ dex}$, $R_s = 1.54^{+0.06}_{-0.03} R_{\odot}$, distance of $447^{+17}_{-7} \text{ pc}$, $A_V = 0.334^{+0.004}_{-0.001}$, and $t_s = 0.38^{+0.28}_{-0.18} \text{ Gyr}$. We point that the age is computed from the GAIA apsis FLAME module, which is obtained by comparing NGTS-33 the T_{eff} and luminosity with the BASTI (Hidalgo et al. 2018) solar metallicity stellar evolution models. ARIADNE computed stellar parameters are: $T_{\text{eff}} = 7437 \pm 72$, $\log g = 4.26 \pm 0.28 \text{ dex}$, $R_s = 1.47 \pm 0.06 R_{\odot}$, $M_s = 1.60 \pm 0.11 M_{\odot}$, $\rho_* = 0.71 \pm 0.12 \text{ g cm}^{-3}$, distance of $448.4 \pm 7.3 \text{ pc}$, $A_V = 0.53 \pm 0.11$, and $t_s = 0.14 \pm 0.12 \text{ Gyr}$. Fig. 6 shows the BT-Settl best-fitting SED model to the archival photometry with adopted median and $1-\sigma$ posteriors distributions for the NGTS-33 stellar parameters shown in Table 4.

We have also attempted to measure NGTS-33 atmospheric properties (T_{eff} , $[\text{Fe}/\text{H}]$, $\log g$, $\sin i_*$) from co-added HARPS spectra using SPECIES⁴ (Soto & Jenkins 2018), a code that estimates atmospheric parameters from high-resolution spectra. However, the code could not converge due to a combination of factors, including limited spectral features, unresolved spectral lines for abundance measurement via equivalent widths, and a low signal-to-noise ratio (HARPS-SNR ~ 40), partly due to its faint $V \sim 11.5 \text{ mag}$. As a result, we opted for the SED fitting method instead.

3.2.1 Age Estimation

A typical method to estimate stellar ages consists of isochrone constructions through the usage of grids of pre-computed stellar evolutionary models described by stellar physical properties (e.g., T_{eff} , L_* , $[\text{Fe}/\text{H}]$, so forth) that are interpolated to fit a set of observed stellar parameters. Such evolutionary models are rearranged to tracks of fixed ages, named isochrones, from which stellar ages are estimated. Nonetheless, limitations exist to precisely estimate stellar ages through isochrone fitting, given the complexity and strong non-linearity in the process of finding the solution. Therefore, the usage of independent methods such as Gyrochronology as well as probing lithium abundances have been used to increase the confidence on the age limits.

We probed gyro-ages from empirical models by Barnes (2007) (hereafter B07) and Mamajek & Hillenbrand (2008) (here after M08) against our measured photometric projected stellar rotation P_{rot} from § 3.1. The models provide ages as a function of rotation period and B-V colour, from which NGTS-33 is placed between 17 and 41 Myr according to M08 and B07 models, respectively, assuming P_{rot} from Table 4. However, in the case of the 2nd highest peak of $\sim 0.8 \text{ day}$, which is present in some of the TESS sectors (see

³ <https://gea.esac.esa.int/archive/>

⁴ <https://github.com/msotov/SPECIES>

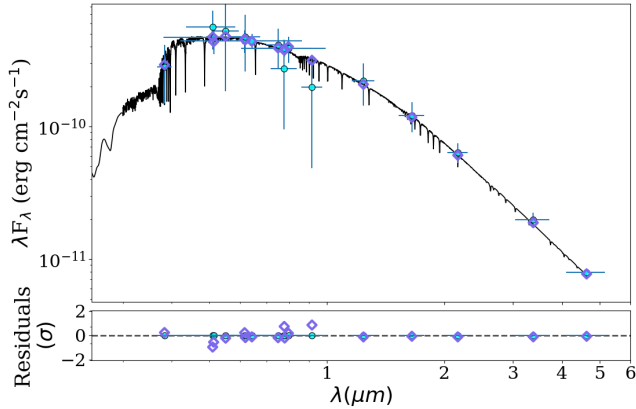


Figure 6. Top: The best-fitting spectral energy distribution model (black line) based on BT-Settl models given the NGTS-33 photometric data (cyan points) and their respective bandwidths shown as horizontal errorbars. Purple diamonds represent the synthetic magnitudes centred at the wavelengths of the photometric data from Table 4. **Bottom:** residuals to the best fit in σ units.

§ 3.1), the gyro-ages from M08 and B07 would be about 24 and 58 Myr, respectively.

Membership of a star within a cluster or association can allow for more precise constraints to be placed on its bulk properties such as age and metallicity, through an ensemble analysis of all stars in the same group. Using GAIA DR2 data, NGTS-33 was highlighted by Cantat-Gaudin et al. (2019) as a likely member (71% likelihood) of Population V in the young Vela-Puppis region, a cluster of stars with similar kinematics which sit nearby the large Vela OB2 association. Through comparison to PARSEC isochrones ($Z=0.019$) this population was found to have an age of ~ 20 -35 Myr, further supporting the younger age derived from gyrochronology. Such youth is also supported by NGTS-33 also being included in the selection of young upper-main sequence stars derived by Zari et al. (2018), however a precise age for this star was not given in this work.

Finally, we searched the NGTS-33 coadded spectrum for any signs of lithium lines as its abundance is associated to young stellar ages. Due to Li volatility with temperature, its abundance is depleted quickly in stellar atmospheres within the first hundred million years of the star lifetime, hence the existence of photospheric Li could place age limits to the star (e.g., see Christensen-Dalsgaard & Aguirre 2018). Li lines were probed across the coadded spectra, particularly around the strong Li resonant doublet at 6707.775 Å and 6707.926 Å, however, possibly due to the fast rotating nature of the host, hence high degree of line blending, no clear evidence of Li was detected at the 17 ppt precision around the doublet. Therefore, although ARIADNE’s age of 0.14 ± 0.12 Gyr is in agreement to other dating methods, we adopted an age upper limit of ~ 50 Myr given the evidences from the literature (Zari et al. 2018; Cantat-Gaudin et al. 2019), the agreement with ARIADNE age estimate as well as our analysis based on Gyrochronology. A lower age limit of ~ 10 Myr is based on planet structure models is discussed in § 4.2.

Table 4. Stellar Properties for NGTS-33

| Property | Value | Source |
|--------------------------------------|---|-----------|
| Astrometric Properties | | |
| R.A. | 07 ^h 11 ^m 20 ^s .0004 | GAIA |
| Dec | −35°51′1″.8648 | GAIA |
| 2MASS I.D. | J07112000-3551019 | 2MASS |
| TIC I.D. | 97921547 | TIC |
| GAIA DR3 I.D. | 5590415817155428224 | GAIA |
| Parallax (mas) | 2.262 ± 0.012 | GAIA |
| $\mu_{R.A.}$ (mas y^{-1}) | -4.936 ± 0.013 | GAIA |
| $\mu_{Dec.}$ (mas y^{-1}) | 6.538 ± 0.014 | GAIA |
| Photometric Properties | | |
| V (mag) | 11.458 ± 0.021 | APASS |
| B (mag) | 11.89 ± 0.028 | APASS |
| g (mag) | 11.655 ± 0.014 | APASS |
| r (mag) | 11.425 ± 0.012 | APASS |
| i (mag) | 11.385 ± 0.011 | APASS |
| G (mag) | 11.394 ± 0.003 | GAIA |
| TESS (mag) | 11.101 ± 0.006 | TIC |
| J (mag) | 10.607 ± 0.023 | 2MASS |
| H (mag) | 10.475 ± 0.024 | 2MASS |
| K (mag) | 10.408 ± 0.021 | 2MASS |
| W1 (mag) | 10.366 ± 0.023 | WISE |
| W2 (mag) | 10.381 ± 0.019 | WISE |
| W3 (mag) | 10.508 ± 0.067 | WISE |
| Derived Properties | | |
| ρ_* (g cm^{-3}) | 0.81 ± 0.02 | EMPEROR |
| $\gamma_{RV-HARPS}$ (km s^{-1}) | $18.93^{+0.01}_{-0.07}$ | EMPEROR |
| $\gamma_{RV-CORALIE}$ (km s^{-1}) | $18.72^{+0.02}_{-0.2}$ | EMPEROR |
| $\gamma_{RV-FEROS}$ (km s^{-1}) | $18.90^{+0.07}_{-0.01}$ | EMPEROR |
| σ_{HARPS} (m s^{-1}) | 141^{+13}_{-39} | EMPEROR |
| σ_{FEROS} (m s^{-1}) | $90 \pm^{+33}_{-29}$ | EMPEROR |
| $\sigma_{CORALIE}$ (m s^{-1}) | $299 \pm^{+86}_{-37}$ | EMPEROR |
| P_{rot} (days) | 0.6654 ± 0.0006 | This work |
| T_{eff} (K) | 7437 ± 72 | ARIADNE |
| [Fe/H] | -0.11 ± 0.17 | ARIADNE |
| log g | 4.26 ± 0.28 | ARIADNE |
| Age (Myr) | 10-50 | This work |
| $M_s (M_{\odot})$ | 1.60 ± 0.11 | ARIADNE |
| $R_s (R_{\odot})$ | 1.47 ± 0.06 | ARIADNE |
| Luminosity (L_{\odot}) | 5.91 ± 0.54 | ARIADNE |
| Distance (pc) | 438.5 ± 7.1 | ARIADNE |

2MASS (Skrutskie et al. 2006); TIC v8 (Stassun et al. 2018); APASS (Henden et al. 2015); WISE (Wright et al. 2010); Gaia (Brown et al. 2021)

3.3 Global modelling

We performed the global modelling with the EMPEROR code⁵ (Vines et al. 2023, Pena & Jenkins in prep), a python toolkit that allows for a joint radial-velocity and photometric analysis. EMPEROR is equipped with Gaussian Processes as well as auto-regressive integrated moving average (ARIMA) models that can be added to the cost function as part of the noise model to properly account for both instrumental and/or astrophysical noise. Moreover, EMPEROR flexibility allows the user to choose amongst samplers such as the Markov-Chain Monte Carlo (MCMC; Foreman-Mackey et al. 2013), Parallel Tempering MCMC (PTMCMC), and nested sampling (DYNESTY;

⁵ <https://github.com/ReddTea/astroEMPEROR>

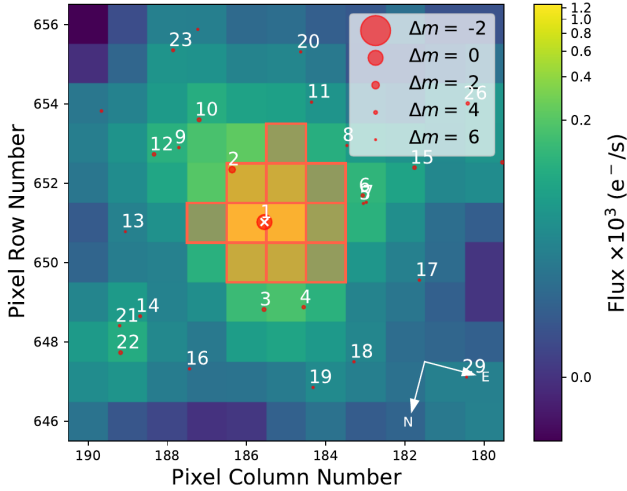


Figure 7. TESS Sector 7 Full-Frame Image cutout (11 x 11 pixels) generated with the `tpfplotter` script described in [Aller et al. \(2020\)](#). NGTS-33b is shown in the centre labeled number 1, followed by UCAC4 271-014742 (number 2), a $V = 13.9$ mag, and $32''$ away from the planet. Our analysis has shown that the star did not contribute significant flux to the aperture, thus negligible dilution was observed in TESS.

[Speagle 2020](#)) to effectively explore the n dimensional parameter space, and reach the optimal solution.

Here we lay out the steps leading to the adopted solution shown in Table 4 and Table 5. We started by running the code with photometry and RV time-series separately, and found a period difference between the datasets of only ~ 8 min. For the global model, multiples runs were executed to probe the prior distributions, the inclusion of an ARIMA model or Gaussian Processes as part of the noise model, linear or quadratic acceleration terms. The adopted solution has been selected upon comparison of every run logarithm Bayesian evidence ($\log Z$) as well as their Bayesian Information Criteria (BIC). Both metrics are frequently used in model selection, where higher $\log Z$ and lower BIC values indicate a preference for a particular model.

As both photometry and RV measurements are commonly impacted by (non-) correlated noise related to the instruments (e.g., nightly drifts, atmospheric turbulence, so forth) and/or the star (e.g., convective overflows, granulation, flares, spots), we found that the runs with GPs included in the photometry time-series yielded low BICs and high $\log Z$ compared to the runs without GPs. In fact, NGTS-33 photometry presented clear signs of periodically modulated activity (see § 3.1) near 0.67d, thus it was necessary to include a global GP Matern kernel to properly model the spot modulated lightcurve. We have also allowed supersampling on the transit model with 20 points per bin for the TESS sector 7 to account for its 30 minute cadence. The Generalised Lomb-Scargle (GLS) periodogram applied to the RV time-series did not show any significant peak at the rotation period, but a highest peak at the planet period 1.83 days (FAP = $\sim 0.1\%$) followed by the 1.39 day peak (FAP = $\sim 8\%$), with latter closer to the first harmonic of the rotation period. Although we are convinced the signal is related to stellar activity, we searched the lightcurves for any evidence of companions and also computed NGTS-33b transit timing variations, where both analysis were against further companions in the system. Finally, we tested the dynamical stability (in § 3.5) assuming a planetary nature for the 1.39d signal, with results consistent with an unstable system,

Table 5. Planetary Properties for NGTS-33b

| Property | Value |
|---|-------------------------------|
| P (days) | 2.827972 ± 0.000001 |
| T_C (BJD _{TDB}) | 2459986.4090 ± 0.0003 |
| T_{14} (hours) | 2.62 ± 0.02 |
| a/R_s | 6.99 ± 0.07 |
| R_p/R_s | 0.1146 ± 0.0004 |
| b | 0.74 ± 0.01 |
| i (deg) | 83.94 ± 0.12 |
| K (m s^{-1}) | 383_{-23}^{+25} |
| e | 0.0 (fixed) |
| ω (deg) | 90 (fixed) |
| M_p (M_J) | 3.63 ± 0.27 |
| R_p (R_J) | 1.64 ± 0.07 |
| ρ_p (g cm^{-3}) | 0.19 ± 0.03 |
| a (AU) | 0.048 ± 0.002 |
| T_{eq}^* (K) | 1991 ± 21 |
| Flux ($\text{erg s}^{-1} \text{cm}^{-2}$) | $(3.56 \pm 1.53) \times 10^9$ |

* Assumed zero Bond albedo

thus we conclude this signal is indeed related to activity, which was modelled with an additional Keplerian function.

Finally, we point out that no dilution terms have been included in the photometry. The brightest ($V = 13.9$ mag) nearby object, UCAC4 271-014742 is $32''$ away and did not affect the transits in the NGTS time-series given its small pixel scale of $\sim 5''/\text{pixel}$. The TESS full frame images (FFI) though, with an on-sky size of $\sim 21''$, would place the contaminant at ~ 1.5 pixels away, leading to a theoretical upper limit flux dilution of 8.75% (Fig. 7), had the contaminant been in the same pixel. However, NGTS and TESS transits have the same depth, thus we conclude that the transits from the TESS mission are not severely affected by dilution. As part of the dilution analysis, we checked our target and the contaminant time-series from NGTS photometry, and ascertain that the transits are on-target. Fig 1 and 2 show the NGTS and TESS detrended lightcurves with their best-fitting models. The RVs are shown in Fig. 3. The parameters of the adopted best-fitting transit and Keplerian models can be found in Table 5, while the second Keplerian associated to stellar activity is in Fig. A1 with parameters shown in Table A2.

We note that two CORALIE RVs highlighted in red squares near phases -0.3 and $+0.45$ located below and above the curve, respectively, disagree significantly with the model. We investigated their BIS, FWHM-CCF as well as the $H\alpha$, Na, Ca line activity indicators and found no evidence that the RVs were affected by stellar activity, thus we kept the points while performing the Global modelling.

3.4 Transit Timing Variation

Transit timing variations (TTVs; [Agol, Steffen, Sari & Clarkson 2005](#)) occur when mid-transit times T_0 deviate from a linear ephemeris model given by $T_n = T_0 + N \times P$, with N and P being the transit number and orbital period, respectively. The most commonly reported scenarios in the literature are: (1) dynamical interactions between the star and the planet, which often results in orbital angular momentum exchanges, leading to orbital decay, and consequently the planet in-falls towards its host star (e.g., WASP-12 [Wong et al. 2022](#)). (2) Planet-planet interactions, specifically near mean motion resonance (MMRs) sites, where the interaction becomes more significant, leading to higher TTV amplitudes (e.g., WASP-47 [Becker et al. 2015](#)). In addition, the interacting bodies frequently show

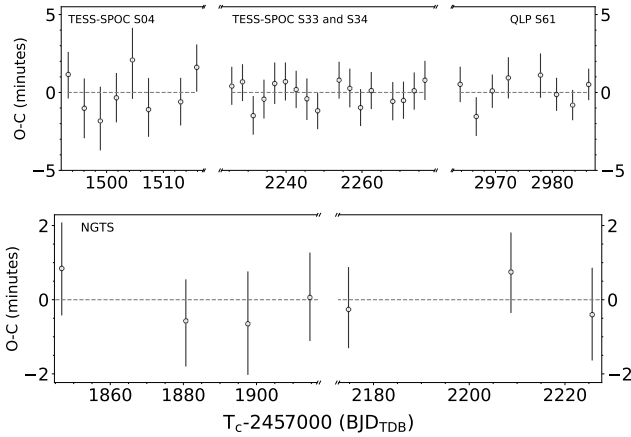


Figure 8. NGTS-33 transit timing variation for the TESS mission (top panel; black open circles) and NGTS mission (bottom panel). The abscissa was zoomed for better visualisation and avoid the large gaps in the time domain. In the top panel, each portion represents a TESS sector with its corresponding reduced pipeline and sector.

anti-correlated TTVs and transit duration variations. In fact, several multi-planet systems in MMRs from the Kepler mission were validated as bonafide planets through the TTV method (Cochran et al. 2011; Gillon et al. 2017; Steffen et al. 2012b), as the host stars brightness were too dim to allow for the necessary RV precision for mass measurements. However, a few systems had their masses estimated from RVs (Barros et al. 2014; Almenara et al. 2018), while others had their masses and eccentricities measured given the precise TTVs data (Lithwick et al. 2012), which revealed the chopping effect, responsible for breaking the M - e degeneracy. Finally, TTVs coupled with RV observations support that hot Jupiters are not part of multi-planet systems (Steffen et al. 2012a; Holczer et al. 2016), with such results placing major constraints on giant planets orbital evolution.

NGTS-33b TTVs were estimated from the GP detrended TESS and NGTS time-series using only transits with full coverage. Each transit mid-time T_n was modelled with the *batman* (Kreidberg 2015) code and final distributions computed with the affine invariant MCMC code implemented in the *emcee* package (Foreman-Mackey et al. 2013). The transit depth $p = \frac{R_p}{R_*}$, normalised semi-major axis $a = \frac{a}{R_*}$ and a linear offset bl around the normalised flux were free parameters in the model. T_n , p , and a were assigned the following uniform priors $\mathcal{U}(T_n-0.1, T_n+0.1)$, $\mathcal{U}(p-0.05, T_n+0.05)$, $\mathcal{U}(a-0.5, a+0.5)$, and $\mathcal{U}(bl-0.1, bl+0.1)$, respectively, with all other parameters being fixed to their medians from Table 5. Finally, a linear ephemeris model was fit to the T_n , where we used 10,000 MCMC steps, with 20% discarded as burn-in. The best-fitting linear model parameters T_0 and P for TESS are given by $T_0 = 1493.2406 \pm 0.0003$ days and $P = 2.82796937 \pm 0.00000089$ days, while for NGTS $T_0 = 1838.2528 \pm 0.0005$ days and $P = 2.8279711 \pm 0.0000049$ days. The OC residuals to the linear ephemeris model for both instruments are shown in Fig. 8, where no evidence for significant TTVs were found, and data made available in table A3.

3.5 NGTS-33 DYNAMICAL STABILITY

Our global model analysis (§ 3.3) revealed a planet signal at 2.83 days and rotation signals at 0.67 days and 0.8 days from the photo-

metric time-series. The RV dataset shows the planet signal followed by an additional peak at 1.39 days, which is twice the photometric rotation period, thus we attributed to stellar activity. In order to provide further credibility that the 1.39 days signal is activity related, we performed dynamical stability simulations to initially (1) assure our solution is dynamically stable and also (2) reject the planetary nature of the 1.39 days signal detected in the RV periodogram. For this purpose, we used REBOUND⁶ (Rein & Liu 2012), an N-body problem solver that integrates particles' motion in time under the influence of larger bodies gravitational potential.

Anchored on our orbital solution laid out in § 3.3 and shown in Table 4, we ran the code up to ~ 100 Myr assuming a 2-body problem made up of our host star and NGTS-33b in order to test the systems stability given our solution. We found no significant changes in its orbital parameters up to this time, otherwise, a larger integration time would have been carried out. Therefore, we stopped the run and assumed the orbital solution is dynamically stable up to ~ 100 Myr.

In the second scenario containing the host star, NGTS-33b, and an inner test particle consistent with the RV signal, i.e., orbital period of 1.39 days and 1.29 M_J . Fig. 9 showed that the semi-major axes and eccentricities were dynamically unstable, with the particle and planet reaching an eccentricity of 1.0 after nearly 140 orbits of NGTS-33b, thus the integration had been stopped due to the chaotic motion. As the particle inclination is unknown, we ran the code multiple times for a 60° - 85° inclination grid with 5° steps. Every run resulted in the system being unstable. For simulations with nearly co-planar orbits, the planet would have likely been detected during our searches for further planets in the photometric time-series. We point out that chaotic simulations are highly sensitive to the initial conditions, i.e., a change in the particle's parameters result in a slight distinct orbital solution, yet every instance yielded unstable parameters, with the particle frequently being ejected at some point in time. Such chaotic behaviour is expected as both NGTS-33b and the particle are HJs near MMRs. Finally, we conclude that our solution described in the global model is dynamically stable, with the second Keplerian being interpreted as stellar activity, rather than a HJ near an MMR state, which is corroborated by the non TTV detection in § 3.4.

4 DISCUSSION

4.1 The transiting hot Jupiter population

Here we place NGTS-33 planetary system in context with the THJ population drawn from the TEPcat catalogue (Southworth 2011). We selected the planets by $P \leq 10$ days and mass range $0.1M_J \leq M \leq 13M_J$, yielding 558 giant planets⁷ on 2 May 2024. Our analysis laid out in § 3 reveals that NGTS-33 is not only the first NGTS discovery of a super-Jupiter around a young fast-rotating host, but also the lowest in density around hot stars ($T_{\text{eff}} \geq 6900\text{K}$), thus making it an interesting target for transmission and emission spectroscopy follow-up with the James Web Space Telescope (JWST; see § 4.3).

Fig. 10 top panel shows the cumulative mass distribution function for the THJ sample, with NGTS-33b belonging to the $\sim 7\%$ most massive THJs discoveries thus far. If we compare it to the

⁶ <https://rebound.readthedocs.io/en/latest/>

⁷ We do not include HATS-70 in the analysis as it is at the boundary between planets and brown dwarfs, with a mass upper limit at $1-\sigma$ of 13.02 M_J

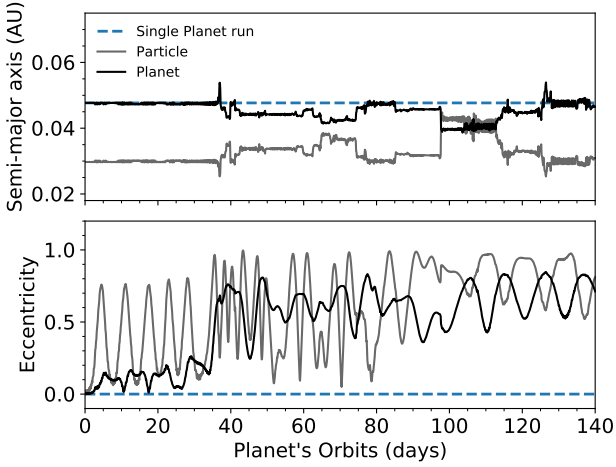


Figure 9. Top: Semi-major axis evolution for NGTS-33 with two planets at orbital periods consistent with NGTS-33b (in black) and a particle similar to a Jupiter planet with $m \sin i = 1.29M_J$ at 1.39 days (in gray). The dashed blue line corresponds to the orbital evolution of the semi-major axis for when NGTS-33b is alone in the system. **Bottom:** Eccentricities evolution. Colours and labels are the same as shown in the top panel.

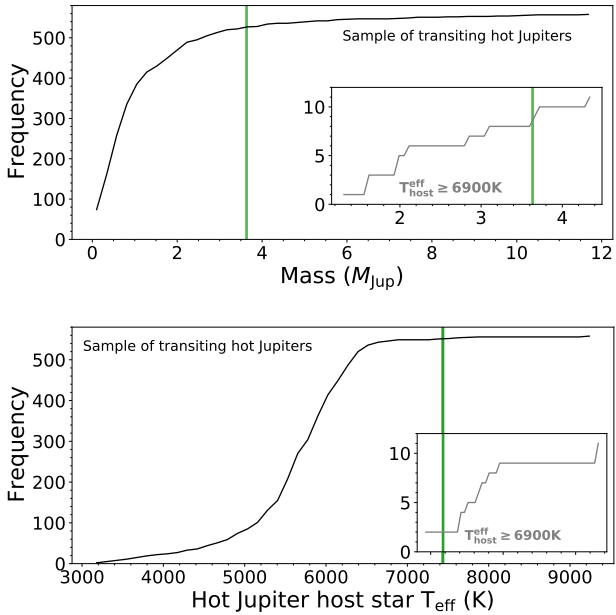


Figure 10. Top: Cumulative distribution functions for the sample of transiting HJs shown as a black solid curve. The green vertical bar highlights NGTS-33b’s mass. The bottom-right plot shows a slice of the cumulative distribution (in gray) containing HJs whose host effective temperatures are above 6900 K. NGTS-33b is not included in either plot. **Bottom:** Same as above for the effective temperatures of transiting HJ hosts.

scarce population of ~ 11 massive THJ around hot hosts, shown in the embedded plot at the lower right, NGTS-33b is amongst the 2nd most massive THJ detected, alongside planets such as MASCARA-1 (Talens et al. 2017), HAT-P-69 (Zhou et al. 2019) and OGLE-TR-L9 (Snellen et al. 2009), with masses of $M_p = 3.7 \pm 0.1 M_J$, $M_p = 3.6 \pm 0.6 M_J$ and $M_p = 4.5 \pm 1.5 M_J$, respectively. We note

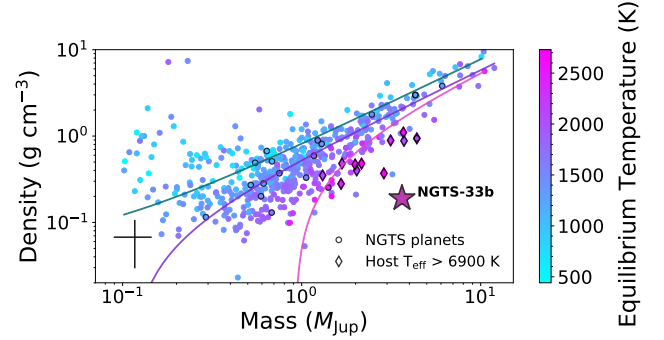


Figure 11. THJ bulk densities as a function of their masses, colour coded by equilibrium temperature. NGTS-33b is represented by the large red star near the image centre towards the bottom right, while the typical uncertainties are shown as a black cross in the bottom left. Black edged diamonds and circles highlight the THJs whose host T_{eff} are greater than 6900 K, and the population of NGTS detected planets, respectively. Best-fitting empirical linear models describing the THJ populations with distinct T_{eq} are highlighted by the cyan, purple and pink colours. See § 4.1 for explanation.

that NGTS-33b mass is in $1-\sigma$ agreement to them, thus placing it amongst the most massive planets around hot hosts. On the other hand, the lower panel of Fig. 10 shows the hosts T_{eff} cumulative distribution function. The rapid growth of the slope centred around G dwarfs and spread over K-type ($\sim 4000\text{--}5250$ K) through late F-type stars (~ 6300 K) represents the majority of THJ hosts. NGTS-33 is highlighted by the green vertical bar, and is amongst the $\sim 2\%$ most massive planet hosts, thus reinforcing the rarity of NGTS-33b detection.

In Fig. 11 we compared NGTS-33b’s bulk density with the THJ population, highlighting other NGTS discoveries as well as giants around as hot hosts ($T_{\text{eff}} \geq 6900$ K; shown as diamonds in the figure). The ρ_p median of similar planets ($2M_J \leq M \leq 5M_J$) is $\sim 1.48 \text{ g cm}^{-3}$, thus placing NGTS-33b’s density $\sim 13\%$ below the median, or $\sim 22\%$ less dense, if compared to the ρ_p median (0.88 g cm^{-3}) of THJ hosted by stars with $T_{\text{eff}} \geq 6900$ K. Such discrepancies may be attributed to NGTS-33b not having undergone significant gravitational collapse due to its young age, thus evidenced by its large radius. However, an irradiated atmosphere, tidal heating during its orbital circularisation or a combination of both could lead to an increase in its radius (see § 4.2), thus significantly reducing its bulk density compared to giants with similar mass.

Finally, in the same figure, distinct THJ groups are observed, which can be distinguished by their T_{eq} and evidenced by the colour gradient. The THJs with higher T_{eq} have significantly lower ρ_p compared to cooler planets, thus providing evidence that their bulk densities are a function of T_{eq} regardless of their thermal evolution processes (e.g., high stellar incidences, tidal heating, so forth). For all planetary masses, the T_{eq} correlates positively with radius, even though more massive planets should be less affected by radius anomaly. This is evidenced by the increasing bulk density with lower T_{eq} regardless of mass bin. A thorough analysis of the T_{eq} , M_p vs ρ_p parameter space may even serve as an independent means to estimate planetary radius for non-transiting planets, where their masses, temperatures could be used to estimate a bulk density, and subsequently their radius. A complete analysis of this problem is beyond the scope of this work, however, we performed a linear fit assuming three THJ populations defined by T_{eq} bins. The lower and upper boundaries were initially motivated by visual inspection, but

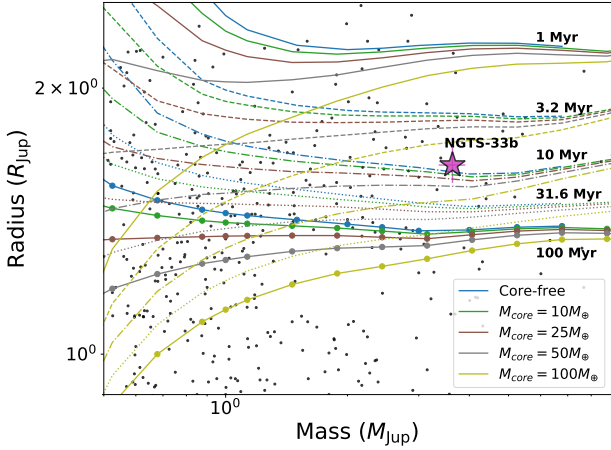


Figure 12. Planet structure models by Fortney et al. (2007). Colour lines represent the same assumed planet core mass, while the lines shapes describes a HJ evolved to a given epoch shown on the right. For instance, the solid lines on the top represent a HJ at 1 Myr, where blue and green lines indicating a core-free and $10M_{\oplus}$ core mass models. NGTS-33b is highlighted by the purple star symbol and black dots are THJs from the TEPIC catalogue.

corroborated by several works showing that the radius anomaly is observed roughly at 1000-1400 K (e.g., Demory & Seager 2011a; Thorngren & Fortney 2018).

Therefore, we adjusted linear empirical models in the form of $\rho_p = A \times M + B$ in order to probe the relationship between ρ_p and M to the three populations defined by $T_{\text{eq}} < 1400$ K (cyan), $T_{\text{eq}} \geq 1400$ K and $T_{\text{eq}} < 2300$ K (purple), and $T_{\text{eq}} \geq 2300$ K (pink), respectively. A and B are free parameters to the model, with best-fitting values given by $0.7706 \pm 0.0004 M_J^{-1}$ and $0.045 \pm 0.001 \text{ g cm}^{-3}$, $0.586 \pm 0.001 M_J^{-1}$ and $-0.065 \pm 0.004 \text{ g cm}^{-3}$, and $0.5858 \pm 0.0001 M_J^{-1}$ and $-0.537 \pm 0.002 \text{ g cm}^{-3}$, respectively, for the three curves defined above by their T_{eq} . The cyan and purple models indicate that giants with lower T_{eq} have larger ρ_p regardless of mass, with a typical ρ_p differences of 0.18, 0.23 and 0.62 g cm^{-3} for giants with masses of 0.6, 1 and $10 M_J$ planets, respectively. Finally, we note that NGTS-33b was not taken into account during the model fitting as its density does not follow any of the three populations.

4.2 Radius Inflation

High incidence stellar flux into a planet's gaseous envelope seems to be the main driving mechanism responsible for the HJs radius anomaly. Demory & Seager (2011b) estimates that an incident flux throughput of $\sim 2 \times 10^5 \text{ W m}^{-2}$ is required for planetary inflation to become observable. Miller & Fortney (2011) points out that the metallicity fraction (Z) also plays an important role, with higher Z fractions reducing the inflation efficiency. In addition, statistical analysis based on planetary thermal evolution models on a sample of 281 HJs (Thorngren & Fortney 2018) showed that the necessary conversion of incident flux into internal heating required to reproduce HJs observed radii, peak's at equilibrium temperature (T_{eq}) ~ 1500 K. Finally, Hartman et al. (2016) shows that HJ radii grows as a function of main sequence star's fractional ages, i.e., as stars age on the main sequence, they brighten up, thus leading to higher planetary irradiation and hence higher T_{eq} of their orbiting planets.

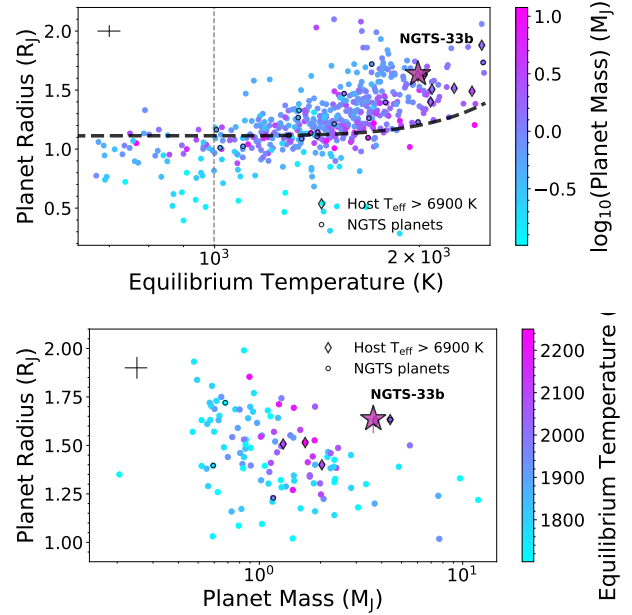


Figure 13. Top: Equilibrium temperature vs planet radius colour-coded by the logarithm of planet mass. Black dashed line represents an inflation-free model for a HJ evolved to 4.5 Gyr with a H/He composition adapted from Thorngren & Fortney (2018). NGTS-33b is displayed by the red coloured star above the model near the image top right. Black cross at the top left corner represents the HJs parameters uncertainties standard deviation, and red open circles marks metal-poor K dwarf stars. **Bottom:** M_p vs R_p colour-coded by T_{eq} showing HJs from the top figure with T_{eq} between 1700-2300 K.

However, alternative scenarios exist to explain HJ radius anomalies, such as star-planet tidal interactions, which lead to internal heating of the planet, thus causing a radius inflation (e.g., see Fortney et al. 2021, for a review).

We probed inflation levels from planetary structure models by Fortney et al. (2007) (hereafter F07). In Figure 12 we show F07 models converted to the appropriate planet-star distance of $\sim 0.02 \text{ AU}$ and evaluated at the model closest in age to NGTS-33b, which shows that its measured radius is above the expected by $\sim 11\%$ - 15% assuming a core-free and $100 M_{\oplus}$ core mass, respectively. Therefore, even at nearly ~ 50 Myr, evolutionary models do not predict such radius, thus, despite its young age, stellar irradiation may be partially contributing to its large size. Had its age been ~ 10 Myr, NGTS-33b radius would be nearly in agreement to F07 models, hence inflation-free, however, such young age is not corroborated by the Gyrochronology and cluster membership analysis (see § 3.2.1), hence it is unlikely that the planet is younger than ~ 10 Myr given the uncertainties in the models and the systems' parameters. Moreover, the absence of infrared excess in the SED fitting (Fig. 6) provides further evidence on NGTS-33 age lower limit as disks tend to disperse around 5-10 Myrs (Hillenbrand 2005). Therefore, we assume an age lower limit about 10 Myr, and conclude that NGTS-33b large radius is likely attributed to a combination of its very young nature and stellar irradiation, causing a radius inflation of $\sim 13\%$ on average.

In Figure 13 top panel we compared NGTS-33b to the THJ population in the R_p vs T_{eq} parameter space colour-coded by the logarithm of their masses. The planet's location, shown as a purple

star symbol, suggests it is inflated compared to the HJ population as well as its counterparts with similar temperatures ($1700 \leq T_{\text{eq}} \leq 2300$ K). However, we point out that the comparison above is partially affected by the HJ population broad ages. Fig. 13 lower panel highlights the THJs in the T_{eq} range in the R_p vs M_{Jup} phase space, where NGTS-33b stands out as a massive and inflated planet. Such result places NGTS-33b as one of the first young and inflated HJ detected, with only 4 THJs younger than 100 Myr reported⁸ thus far (e.g., K2-33 b, TOI-942 b, CoRoT-20 b, and WASP-33 Ab). Therefore, its discovery will add to the small but growing population of young planets, and subsequent follow-up will help place constraints on the formation and evolution of massive and hot systems.

4.3 Is NGTS-33b suitable for atmospheric follow-up with JWST?

The discovery of transiting planets allowed the investigation of their atmospheric abundances, with short period HJs remaining the best targets for atmospheric follow-up. Their high equilibrium temperature ($T_{\text{eq}} \geq 1000$ K) and lower densities ($\rho_p < 0.3 \text{ gcm}^{-3}$), induces scale heights such that the chemistry of inner layers are brought up, thus allowing the investigation of a variate of species by the transmission spectroscopy technique (Seager & Sasselov 2000). On the other hand, the planet's secondary eclipses allows the inference of day-side temperature as well as the albedo/reflectivity through emission spectroscopy. Such techniques have been vastly applied by ground- (e.g., ESPRESSO/VLT, HIRES/Keck) and space-based missions such as the Hubble Space Telescope, Spitzer, and recently, the JWST.

Stevenson et al. (2016) selected 12 objects for JWST follow-up dubbed community targets (CT) based mostly on their properties, where optimal candidates are often quiet ($\log R'_{\text{HK}} \leq -4.8$), short period ($P < 10$ days), bright ($J < 10.5$ mag) and have orbital solutions and masses well-constrained. A high ecliptic latitude ($b > 45^\circ$) is also important as such targets being near or within the continuing viewing zone allow for multiple visits, consequently a higher SNR would be reached. Since NGTS-33b matches several of these criteria, we computed its signal size per scale height defined in Kempton et al. (2018) by assuming a cloud-free atmosphere and constant T_{eq} , which is given by

$$\Delta D = \frac{2k_B T_{\text{eq}} R_p}{\mu g R_S^2} \quad (3)$$

with k_B , μ , and g being the Boltzmann constant, mean molecular weight and the planet's gravity. From Eq. 3 we estimated NGTS-33b ΔD of ~ 53 ppm/H, which is comparable to the lower limit of the community target signal size range of 60-240 ppm/H, thus making NGTS-33b an interesting target for follow-up observations.

We have also computed the transmission and emission spectroscopy metrics TMS and EMS homogeneously from Eq. 1 and Eq. 4 by (Kempton et al. 2018), shown in Fig. 14. Although NGTS-33b seems less favorable for transmission spectroscopy as compared to the HJs and CT targets at similar densities (top left panel), its host sits in an under populated part of the TSM vs T_{eff} parameter space (bottom left panel), thus making the system an interesting candidate for atmosphere characterisation. In addition, the hosts with $T_{\text{eff}} > 6900$ K, mostly left of NGTS-33 are orbited by denser

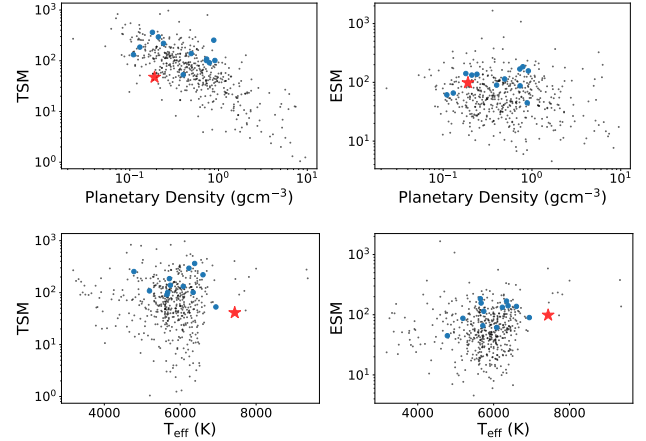


Figure 14. Top: Transmission and emission spectroscopy metrics as a function of planetary density for the transiting HJ sample are shown in black circles, whereas JWST community targets by (Stevenson et al. 2016) are marked by blue circles. NGTS-33b is represented by the big red star. The TSM and ESM were computed homogeneously using the systems properties from the TEPcat catalogue. Bottom: TSM and ESM as a function of host effective temperature. Colour schemes are the same as described in the top panel.

planets ($\rho_p > 0.28 \text{ gcm}^{-3}$), hence distinct atmospheric properties/abundances given their smaller scale heights. The ESM though indicates that NGTS-33b is an interesting target for JWST emission spectroscopy follow-up as its ESM is equivalent to CT and above most of HJ ESMs (top right panel). Similarly to the TSM, ESM vs T_{eff} shows that very few stars populate the hot edge ($T_{\text{eff}} > 6900$ K) of the parameter space. Even though a handful of them (~ 4 out of 11) have been targeted for follow-up, the majority lacks atmospheric characterisation. Therefore, such part of the parameter space remains a golden region for an in-depth JWST atmospheric follow-up.

4.4 NGTS-33b obliquity follow-up

When a transiting planet blocks part of the stellar disc, the spectral line centroids can be shifted, leading to an RV anomaly, well-known as the Rossiter-McLaughlin effect (RM; Trianaud et al. 2009). Such phenomenon allows us to measure the obliquity angle between the planet's orbital axis to that of the star. In fact, the technique was responsible to reveal that a handful of close-in massive giants have non-zero obliquities (e.g., KELT-17b, MASCARA-1b, TOI-1431b), with some even in retrograde orbits (HAT-P-14b; Winn et al. 2011). In addition Winn et al. (2011) points that cool hosts tend to have planets with low obliquities, compared to hot hosts, hence indicating that even THJs may have undergone distinct migration channels, yet non-zero obliquities could have also been a result of primordial misalignment between the central star and its protoplanetary disc (Albrecht et al. 2022). Therefore, measuring the obliquity of NGTS-33b might provide valuable information on massive planetary systems evolution history.

The relatively large star-to-planet radius ratio and the host fast spinning rate indicates that NGTS-33 is a good candidate for in-transit RV monitoring. The RM amplitude can be estimated by

$$A_{\text{RM}} = \frac{2}{3} \left(\frac{R_p}{R_*} \right)^2 v \sin i_* \sqrt{1 - b^2} \quad (4)$$

⁸ <https://exoplanet.eu/>

where b is the planet's impact parameter. An $A_{\text{RM}} \sim 660.56 \text{ ms}^{-1}$ is expected for the planet, assuming $v \sin i_* \sim 111.87 \text{ km s}^{-1}$ from P_{rot} and R_p . Such value is ~ 1.7 higher than the planet induced RVs, which is explained by the relatively large coverage of the stellar disc by the planet, but mainly due to the star's extremely short rotation period of 0.67 days. In addition, the system's obliquity could possibly be measured directly through Doppler tomography (Cameron et al. 2010; Watanabe et al. 2022). Finally, Gaudi & Winn (2007) showed that, for small planets of mass M on an edge-on circular orbit with period P , the ratio between the RM amplitudes and that of the planet induced velocity can be approximated by

$$\frac{A_{\text{RM}}}{K} \sim 0.3 \left(\frac{M}{M_{\text{Jup}}}\right)^{-1/3} \left(\frac{P}{3 \text{ days}}\right)^{1/3} \left(\frac{v \sin i_*}{5 \text{ km s}^{-1}}\right) \quad (5)$$

Using our derived values for M , P and $v \sin i_*$, we would expect an even larger ratio of about 4.3. Nonetheless, NGTS-33b's RM effect is expected to be above the planet's induced velocity, thus it can easily be measured with high-resolution spectrographs ($R \geq 60,000$).

5 CONCLUSION

We report the discovery of NGTS-33b, a super-Jupiter with mass, radius, and bulk density of $3.63 \pm 0.27 M_J$, $1.64 \pm 0.07 R_J$ and $0.19 \pm 0.03 \text{ g cm}^{-3}$, respectively. The planet orbits a massive A9V star every 2.83 days, whose mass, radius and effective temperature are of $1.60 \pm 0.11 M_S$, $1.47 \pm 0.06 R_S$, and $7437 \pm 72 \text{ K}$, respectively. NGTS-33 is one of the youngest hosts discovery thus far, having an age of 10-50 Myr, and the 5th hottest star hosting a THJ. In addition, membership analysis indicates that NGTS-33 may be part of the Vela OB2 association. In fact, NGTS-33 is not only young but also rare, laying amongst the 2% most massive THJ hosts, whereas the planet represents the $\sim 7\%$ most massive THJs currently detected. Moreover, planetary structure models show that NGTS-33b's radius is likely inflated by up to $\sim 15\%$. Such is evidenced by its extremely low density compared to THJ of similar M and T_{eq} . In fact, NGTS-33b's bulk density is nearly 13% lower than that expected for its mass, thus likely a combination of its large radius due to youth and its irradiated atmosphere. In addition, we noticed what may be three populations of THJs distinguished by their T_{eq} , with boundaries at $T_{\text{eq}} \sim 1400 \text{ K}$ and $\sim 2300 \text{ K}$. Giants with $T_{\text{eq}} < 1400 \text{ K}$ were found to have larger ρ_p independent of mass, thus implying that their ρ_p are, to first order, a function of T_{eq} regardless of thermal evolution processes. Empirical linear models fitted to cooler ($T_{\text{eq}} < 1400 \text{ K}$) and warmer ($1400 \leq T_{\text{eq}} < 2300 \text{ K}$) giants populations showed a difference in ρ_p of about 0.18, 0.23 and 0.62 g cm^{-3} for giants with masses of 0.6, 1 and $10 M_J$ planets, respectively.

The ESM computed for NGTS-33b puts it near the JWST community targets boundary, and one of the lowest in density amongst hot hosts, thus making it a suitable candidate for emission spectroscopy with JWST. Additionally, NGTS-33's fast spin combined with the planet's large radius, gives it an expected RM amplitude of $\sim 660.56 \text{ m s}^{-1}$, i.e. 1.7 times that of the RV induced variation generated by the planet, thus making it a good candidate for obliquity studies also.

Finally, with only 11 detections thus far, the number of massive Jupiters hosted by hot stars ($T_{\text{eff}} \geq 6900 \text{ K}$) is strikingly scarce, thus the discovery of NGTS-33b will significantly add to the small but increasing population of massive THJs, which will help place further constraints on current formation and evolution models for such planetary systems.

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DATA AVAILABILITY

The data underlying this article are made available in its online supplementary material.

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APPENDIX A: EXTRA TABLES AND FIGURES

- A1** ARIADNE priors for the stellar characterisation
- A2** Global Modelling: Activity Signal
- A3** Transit Timing Variation data
- A4** Spot-crossing events on NGTS-33 and periodicity analysis on nearby object UCAC4 271-014742

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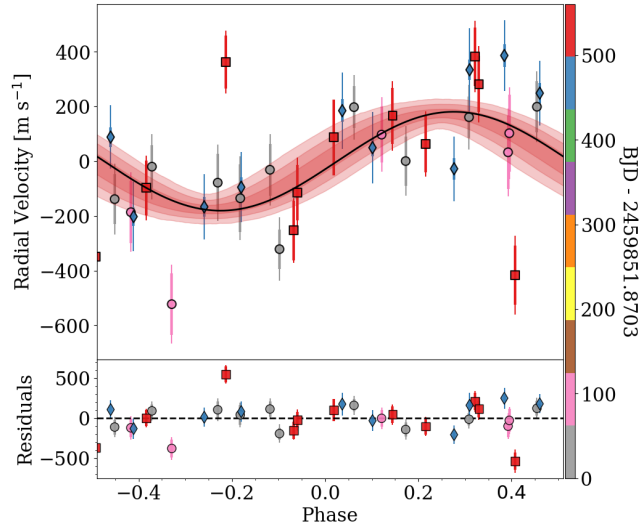


Figure A1. Top: RV phase-folded to the second Keplerian values associated to the stellar activity signal with fixed values from Table A2. Bottom: residuals to the best fit model.

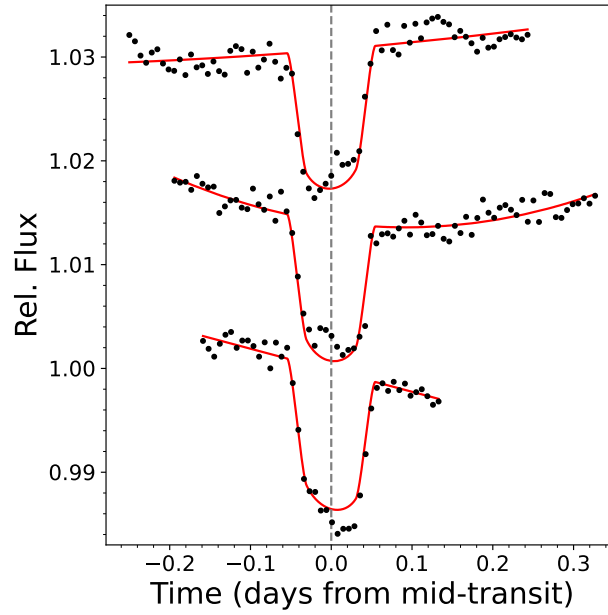


Figure A2. TESS-SPOC non-detrended time-series (in black) showing 3 potential spot-crossing events and stellar activity. A polynomial function was added to the transit model for visualisation purposes (in red). QLP and CDIPS lightcurves were visually check, thus roughly showing the same spot-crossing patterns. Time flows from top to bottom, with the first two events from sector 33, while the transit at the bottom being from sector 34.

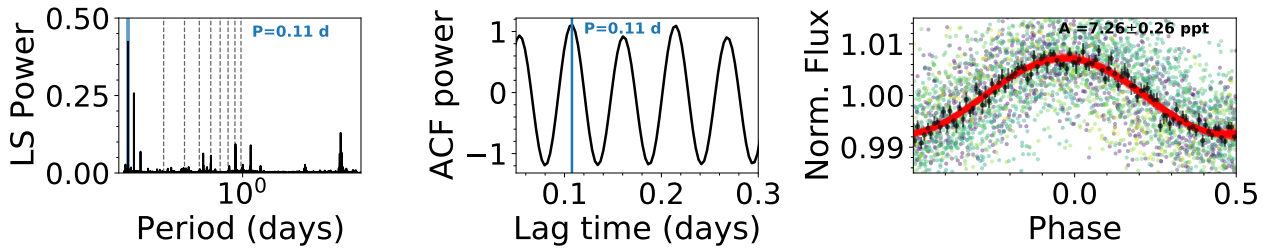


Figure A3. Rotation analysis on UCAC4 271-014742, a known pulsating variable star of $V = 13.9$ mag, period of 0.097174 day from GAIA, and 32" away from NGTS-33. See Figure 5 for comparison and § 3.3 and 3.1 for more information.

Table A1. NGTS-33 ARIADNE priors

| Parameters | Prior | Hyperparameters |
|------------------|---------|-----------------------------|
| T_{eff} | Normal | (7434, 100 ²) |
| $\log g$ | Normal | (4.3, 0.4 ²) |
| [Fe/H] | Normal | (-0.13, 0.23 ²) |
| Distance | Normal | (438, 10 ²) |
| R_s | Normal | (1.48, 0.5 ²) |
| A_V | Uniform | (0.00, 1.02) |

Table A2. Properties for the second Keplerian

| Property | Value |
|------------------------|------------------|
| P (days) | 1.391558 (fixed) |
| K (m s ⁻¹) | 176±54 |
| e | 0.0 (fixed) |
| ω (deg) | 90 (fixed) |
| M_o (deg) | 64 (fixed) |

Table A3. NGTS-33 TTV data

| Time (days; BJD _{TDB}) | OC (minutes) | low error | upper error | Pipeline |
|----------------------------------|--------------|-----------|-------------|-----------|
| 2458493.239828 | 1.15399 | 1.54222 | 1.45155 | TESS-SPOC |
| 2458496.067799 | -1.01492 | 1.92430 | 1.91326 | TESS-SPOC |
| 2458498.895770 | -1.82914 | 1.89144 | 2.20077 | TESS-SPOC |
| 2458501.723741 | -0.34039 | 1.57699 | 1.59344 | TESS-SPOC |
| 2458504.551712 | 2.08556 | 2.49663 | 2.06386 | TESS-SPOC |
| 2458507.379683 | -1.10107 | 1.74482 | 2.02213 | TESS-SPOC |
| 2458513.035625 | -0.60221 | 1.51767 | 1.54191 | TESS-SPOC |
| 2458515.863596 | 1.61295 | 1.56667 | 1.47080 | TESS-SPOC |
| 2459225.684317 | 0.40665 | 1.20163 | 1.24230 | TESS-SPOC |
| 2459228.512288 | 0.68259 | 1.23309 | 1.13504 | TESS-SPOC |
| 2459231.340259 | -1.48732 | 1.21970 | 1.25541 | TESS-SPOC |
| 2459234.168230 | -0.43365 | 1.24079 | 1.25539 | TESS-SPOC |
| 2459236.996201 | 0.57253 | 1.31606 | 1.35225 | TESS-SPOC |
| 2459239.824172 | 0.69138 | 1.20454 | 1.23394 | TESS-SPOC |
| 2459242.652143 | 0.18517 | 1.17847 | 1.20931 | TESS-SPOC |
| 2459245.480114 | -0.40457 | 1.36060 | 1.30785 | TESS-SPOC |
| 2459248.308085 | -1.17481 | 1.18139 | 1.15836 | TESS-SPOC |
| 2459253.964027 | 0.78740 | 1.18390 | 1.18485 | TESS-SPOC |
| 2459256.791998 | 0.26238 | 1.21833 | 1.27035 | TESS-SPOC |
| 2459259.619969 | -0.97629 | 1.18017 | 1.19100 | TESS-SPOC |
| 2459262.447940 | 0.12103 | 1.18787 | 1.19200 | TESS-SPOC |
| 2459268.103882 | -0.57445 | 1.21199 | 1.24292 | TESS-SPOC |
| 2459270.931853 | -0.51148 | 1.18199 | 1.20794 | TESS-SPOC |
| 2459273.759824 | 0.11163 | 1.21530 | 1.17389 | TESS-SPOC |
| 2459276.587795 | 0.78147 | 1.26831 | 1.24836 | TESS-SPOC |
| 2459963.784748 | 0.52137 | 1.14355 | 1.13239 | QLP |
| 2459966.612719 | -1.54366 | 1.24778 | 1.24212 | QLP |
| 2459969.440690 | 0.10603 | 1.09343 | 1.04511 | QLP |
| 2459972.268661 | 0.93827 | 1.32315 | 1.32652 | QLP |
| 2459977.924603 | 1.11141 | 1.45005 | 1.39217 | QLP |
| 2459980.752574 | -0.13346 | 1.04637 | 1.07595 | QLP |
| 2459983.580545 | -0.80981 | 0.97173 | 0.97677 | QLP |
| 2459986.408516 | 0.51174 | 1.00639 | 1.01724 | QLP |
| 2458846.736203 | 0.843355 | 1.267368 | 1.241354 | NGTS |
| 2458880.671855 | -0.571765 | 1.229419 | 1.120578 | NGTS |
| 2458897.639681 | -0.649302 | 1.378999 | 1.412332 | NGTS |
| 2458914.607507 | 0.060029 | 1.175076 | 1.212128 | NGTS |
| 2459174.780839 | -0.262582 | 1.045301 | 1.142524 | NGTS |
| 2459208.716491 | 0.745968 | 1.103477 | 1.067075 | NGTS |
| 2459225.684317 | -0.402598 | 1.236785 | 1.264854 | NGTS |