NGTS-6b: An Ultra Hot-Jupiter Orbiting a Metal-rich star

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ABSTRACT

We report the discovery of a new ultra hot Jupiter from the Next Generation Transit Survey. NGTS-6b orbits its star with a period of 21.17 h, and has a mass and radius of $1.330^{+0.024}_{-0.028} M_J$ and $1.271^{+0.197}_{-0.188} R_J$ respectively. Conforming to the currently known small population of ultra hot Jupiters, the planet is also found to orbit a metal-rich star ([Fe/H] = $+0.11 \pm 0.09$ dex). Photoevaporation models suggest the planet should have lost 5% of its gaseous atmosphere over the course of the 9.6 Gyrs of evolution of the system. NGTS-6b adds to the small, but growing, list of ultra-short period gas giant planets, and will help us to understand the dominant formation and evolutionary mechanisms that govern this population.

Key words: Planetary systems – Planets and satellites:detection – Planets and satellites:gaseous planets

1 INTRODUCTION

Over the last few years, ultra-short period (USP) planets have emerged as an important sub-population of planets, characterized solely by their proximity to the host star ($P_{\text{orb}} < 1$ day). The majority of the population have been detected by space-based instruments, particularly CoRoT (CoRoT Team 2016) and Kepler (Borucki et al. 2010), due to the tendency of the population to heavily favour small physical sizes and masses, and therefore large densities (Charpinet et al. 2011; Pepe et al. 2013; Guenther et al. 2017; Santerne et al. 2018; Crida et al. 2018; Espinoza et al. 2019).

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Ground-based programs have found it difficult to detect these systems, both by radial-velocity measurements and transits, since both are affected by the nightly window function problem. Also, the formation mechanism seems to favour small planets, and therefore both the radial-velocity and transit signals are also small, making them harder to detect. However, on the plus side, other biases work in favour of these methods, since the radial-velocity amplitude for a given star-planet systems increases with decreasing orbiting period, and the probability of transits rises, as well as the frequency of transits. In fact, although small USP super-Earths ($R_p \leq 2R_\oplus$) are more common than larger planets by a factor of 5 (Winn et al. 2018), a number have been detected from ground-based photometric surveys and confirmed by radial-velocity measurements, with the majority of this small sample being hot Jupiters (HJs; Southworth et al. 2009, 2015; Penev et al. 2016; Oberst et al. 2017). The population in between these two extremes of hot super-Earths and HJs have remained fairly elusive.

Models of the population of USP planets employ either photoevaporation or Roche Lobe overflow of a migrating more massive planet, which strips the planet of its gaseous envelope (Valsecchi et al. 2014; Jackson et al. 2016). The migration occurs either as disk migration (Mandell et al. 2007; Terquem 2014) or by dynamical interactions (Fabrycky & Tremaine 2007). In situ formation has also been invoked to describe the population (Chiang & Laughlin 2013). The first ultra hot Jupiter (UHJ; gas giants with an orbit $\leq 0.05$ AU) was discovered (Fabrycky et al. 2010), but has led to a deeper understanding of these models since a lack of explanation of why it has not lost the majority of its gaseous envelope provides strong constraints on the history of its dynamical evolution (Essick & Weinberg 2015). Subsequent and forthcoming discoveries of UHJ planets are providing critical constraints on the formation and evolution of close-in planets.

The Next Generation Transit Survey (NGTS; Chazelas et al. 2012; Wheatley et al. 2013; McCormac et al. 2017; Wheatley et al. 2018) has now been fully operational for over two years, announcing the discovery of 5 new planets (Bayliss et al. 2018; Raynard et al. 2018; Günther et al. 2018; West et al. 2018; Eiglmüller et al. submitted), which include a dense sub-Neptune (NGTS-4b), a sub-Jovian planet (NGTS-5b), a giant planet transiting an M dwarf star (NGTS-1b), and some new HJs (NGTS-2h, NGTS-3Ab). The dense sampling of NGTS fields over long observing seasons, combined with the high precision of individual images ($\sim 0.001$ magnitudes), allows the detection of not only smaller transiting planets, but also those with very short periods. In this work, we report the discovery of a new UHJ, NGTS-6b, orbiting the star NGTS-6. The paper is organised as follows; in § 2 we describe the NGTS observations that led to the discovery, with follow-up photometry from SAAO discussed in § 2.3 and the follow-up spectroscopy from FEROS and CORALIE discussed in § 2.4. We analyse the nature of the star in § 3 and discuss the modeling in § 4. Our conclusions are highlighted in § 5.

Figure 1. Light curve of NGTS photometry for NGTS-6 phase folded to the planets orbital period. The grey circles show the photometry observations binned to 10 minute cadence and the figure is zoomed to highlight the transit. The solid blue line and blue shaded regions represent the median, 1, 2, or 3σ confidence levels, respectively, of the best posterior model. Bottom: The residuals of the fit in ppm.
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0.96 0.98 1.00 1.02 1.04
Relative flux

0.04 0.02 0.00 0.02 0.04
20000 0 20000
Residuals (ppm)

2.3 SAAO Photometric Follow Up

Three transit light curves were obtained with the 1.0-m Elizabeth telescope at the South African Astronomical Observatory (SAAO) and one of the SHOC frame-transfer CCD cameras, “SHOC’n’awe” (Coppejans et al. 2013). The transits were collected on 2018 October 7 in V band (240 × 60 second exposures), and on 2018 November 14 and 15 in I band (470 × 30 second and 340 × 30 s exposures respectively). The data were reduced with the local SAAO SHOC pipeline, which is driven by PYTHON scripts running IRAF tasks (PYFLITS and PYRAF), and incorporating the usual bias and flatfield calibrations. Aperture photometry was performed using the Starlink package AUTOPHOTOM.

Differential photometry was performed on each light curve using 2 reference stars and altering the size of the aperture to reflect the sky conditions (4px for the V band light curve, 5px for the I band light curve on 2018 Nov 14 and 3px for the light curve obtained on the following night when the conditions were considerably better).

We show phase folded light curves of the three SAAO transit events in Figure 3 with their respective models and confidence regions. The complete light curve for all instruments is shown in Table 1.

2.4 Spectroscopic Follow Up

We obtained multi-epoch spectroscopy for NGTS-6 with two different fiber-fed high precision échelle spectrographs: CORALIE and FEROS. Both are located at the ESO La Silla Observatory in Chile. CORALIE is mounted on the 1.2-m Leonard Euler telescope and has a spectral resolution of $R = 100,000$ (Queloz et al. 2001b). FEROS is mounted on the 2.2-m MPG/ESO telescope with a spectral resolution of $R = 48,000$ (Kaufer et al. 1999). The spectral observations were taken between October 23 2018 and January 8 2019 for CORALIE and December 23 2018 and January 2 2019 for FEROS.

The CORALIE data were reduced using the standard data reduction pipeline (Queloz et al. 2001b) and the radial velocities were calculated by cross-correlation with a binary G2 mask. The first 20 orders of the spectrum were discarded in the cross-correlation analysis as they contain little signal.

1 https://mast.stsci.edu/tesscut
We calculated the Pearson r coefficient to be fit and a radial-velocities are shown in Figure 4 along with a linear on the validity of the planet interpretation of the radial- et al. 2009). Any correlation between radial-velocity mea- surements color coded by observation time. Circles are CORALIE and upside-down triangles are FEROS datapoints. The blue solid line is a linear fit and the shaded region show the 2σ confidence region. No correlation is detected.

All the CORALIE spectra were also stacked to make a high signal-to-noise spectrum for spectral analysis as presented in Sect. 3. FEROS data were reduced with the CERES pipeline (Brahm et al. 2017). CERES also calculates the cross-correlation function (CCF) using the reduced FEROS spectra and a binary G2 mask for each epoch and afterwards, depending on moonlight contamination, a single or double Gaussian is then fitted to find the radial velocity (depending on moonlight contamination). In the cases where the single or double Gaussian fits were unsatisfactory, a 4th order spline was fitted to find the radial velocity instead. The radial velocities from CORALIE and FEROS are shown in Table 2 along with the uncertainties and bisector velocity span. We present a total of 21 radial velocity data points, 11 of which were taken with CORALIE and 10 with FEROS.

As a first check we searched for a correlation between the radial-velocity data and the bisector velocity span, which was calculated using the CCF’s that were constructed to measure the velocity in the first place (see for example Boisse et al. 2009). Any correlation between radial-velocity measurements and the bisector velocity span would cast doubts on the validity of the planet interpretation of the radial-velocity variation (Queloz et al. 2001a). The bisector and radial-velocities are shown in Figure 4 along with a linear fit and a 2σ confidence region, with no correlation detected. We calculated the Pearson r coefficient to be 0.05, which reaffirms our claim of no significant linear correlation being present.

### 3 STELLAR PARAMETERS

Given the host star is relatively faint (V = 14.087), the high-resolution echelle spectra used for the calculation of the radial velocity measurements would not allow a well constrained solution from the SPECIES code (Soto & Jenkins 2018) to be found for the stellar bulk parameters. Therefore, we used the empirical SpecMatch tool (Yee et al. 2017) with the combined CORALIE spectra. We adopted the stel- lar radius provided by the Gaia DR2 catalogue and used it to calculate the host star’s mass using the stellar density cal-

| BJD (-2,450,000) | Relative Flux | Relative Flux error | INST |
|------------------|--------------|---------------------|------|
| 8200.55123       | 1.02219      | 0.01669             | NGTS |
| 8200.55138       | 0.96602      | 0.01678             | NGTS |
| 8200.55153       | 0.98588      | 0.01696             | NGTS |
| 8200.55168       | 1.02056      | 0.01705             | NGTS |
| 8200.55183       | 0.98613      | 0.01691             | NGTS |

### Table 2. CORALIE and FEROS Radial Velocities for NGTS-6

| BJD (-2,450,000) | RV (km s⁻¹) | σRV (km s⁻¹) | BIS | INST |
|------------------|-------------|--------------|-----|------|
| 8415.71          | -19.526     | 0.165        | -0.420 | CORALIE |
| 8418.74          | -18.633     | 0.104        | -0.109 | CORALIE |
| 8454.65          | -19.324     | 0.125        | 0.059  | CORALIE |
| 8472.59          | -18.856     | 0.109        | 0.154  | CORALIE |
| 8472.75          | -19.064     | 0.124        | 0.125  | CORALIE |
| 8475.69          | -19.333     | 0.102        | —     | CORALIE |
| 8475.79          | -19.264     | 0.110        | —     | CORALIE |
| 8481.71          | -19.396     | 0.098        | -0.411 | CORALIE |
| 8481.81          | -19.494     | 0.102        | 0.335  | CORALIE |
| 8492.69          | -19.019     | 0.086        | -0.181 | CORALIE |
| 8492.73          | -19.105     | 0.098        | -0.061 | CORALIE |
| 8481.85          | -19.536     | 0.047        | 0.929  | FEROS  |
| 8480.75          | -19.196     | 0.026        | 0.064  | FEROS  |
| 8480.73          | -19.033     | 0.022        | -0.026 | FEROS  |
| 8484.71          | -19.189     | 0.016        | 0.050  | FEROS  |
| 8478.79          | -18.746     | 0.028        | 0.517  | FEROS  |
| 8478.60          | -19.052     | 0.025        | 0.068  | FEROS  |
| 8478.81          | -18.946     | 0.043        | 0.882  | FEROS  |
| 8478.62          | -18.874     | 0.026        | -0.054 | FEROS  |
| 8483.84          | -19.103     | 0.026        | -0.115 | FEROS  |
| 8483.67          | -19.434     | 0.017        | 0.002  | FEROS  |

All the CORALIE spectra were also stacked to make a high signal-to-noise spectrum for spectral analysis as presented in Sect. 3. FEROS data were reduced with the CERES pipeline (Brahm et al. 2017). CERES also calculates the cross-correlation function (CCF) using the reduced FEROS spectra and a binary G2 mask for each epoch and afterwards, depending on moonlight contamination, a single or double Gaussian is then fitted to find the radial velocity (depending on moonlight contamination). In the cases where the single or double Gaussian fits were unsatisfactory, a 4th order spline was fitted to find the radial velocity instead. The radial velocities from CORALIE and FEROS are shown in Table 2 along with the uncertainties and bisector velocity span. We present a total of 21 radial velocity data points, 11 of which were taken with CORALIE and 10 with FEROS. As a first check we searched for a correlation between the radial-velocity data and the bisector velocity span, which was calculated using the CCF’s that were constructed to measure the velocity in the first place (see for example Boisse et al. 2009). Any correlation between radial-velocity measurements and the bisector velocity span would cast doubts on the validity of the planet interpretation of the radial-velocity variation (Queloz et al. 2001a). The bisector and radial-velocities are shown in Figure 4 along with a linear fit and a 2σ confidence region, with no correlation detected. We calculated the Pearson r coefficient to be 0.05, which reaffirms our claim of no significant linear correlation being present.

### 3.1 SED Fitting and Dilution

We identified a neighbouring source that could be contaminating our photometry, and therefore in order to determine the level of dilution from this source, we performed SED fitting of both stars using the PHOENIX v2 models (Husser et al. 2013). This was done following a method similar to Gillen et al. (2017), by firstly generating a grid of bandpass calculated during the global modeling, as described in Section 4.2. We found the host star NGTS-6 to be a metal-rich K dwarf, with an effective temperature of 4410 ± 70 K, a log g of 4.63 ± 0.12g/cm³, and a [Fe/H] of 0.11 ± 0.09 dex. The Gaia radius for this star is 0.656±0.028 R⊙ and we calculated its mass to be 0.7876±0.0163 M⊙. We show the host star’s catalogue information and stellar parameters in Table 3.
Gaia DR2 values calculated by Bailer-Jones et al. (2018). To sample the posterior distribution, we used emcee (Foreman-Mackey et al. 2013) to create a Markov Chain Monte Carlo (MCMC) process for our fitting. In this process we used 100 walkers for 50,000 steps and discarded the first 10,000 as a burn in. The best fitting SED model for NGTS-6 is shown in Fig. 5.

To estimate the level of dilution in each bandpass we convolved the SED model for each star with the specified filter, taking the ratio of the measured synthetic fluxes as the dilution value. In order to sample the full range of dilutions and thus provide an informative prior we draw our SED models directly from the posterior distribution for each star. The calculated dilutions are $D_{\text{NGTS}} = 0.0541^{+0.0058}_{-0.0053}$, $D_{\text{SAAOV}} = 0.0235^{+0.0033}_{-0.0029}$, $D_{\text{SAAOI}} = 0.0809^{+0.0079}_{-0.0082}$, $D_{\text{TESS}} = 0.0791^{+0.0085}_{-0.0077}$. With these results we generate priors for the dilution in our lightcurves, which are used in the transit fitting.

4 DATA MODELING

4.1 Pure Radial Velocity Modelling

Firstly, a pure radial velocity search and model fit was made using the EMPEROR algorithm (Peña Rojas & Jenkins 2018). EMPEROR is a public, python-based code that is designed to search for small signals in radial-velocity data using Bayesian modeling techniques and MCMC tools. The algorithm allows for correlated noise models to be incorporated into the modeling, in particular moving averages of order selected by the user. The code uses the affine-invariant emcee sampler in parallel tempering mode to efficiently sample highly multi-modal posteriors.

In order to first test if the signal was present in the data we used the EMPEROR algorithm (Peña Rojas & Jenkins 2018). EMPEROR is a public, python-based code that is designed to search for small signals in radial-velocity data using Bayesian modeling techniques and MCMC tools. The algorithm allows for correlated noise models to be incorporated into the modeling, in particular moving averages of order selected by the user. The code uses the affine-invariant emcee sampler in parallel tempering mode to efficiently sample highly multi-modal posteriors.

In order to first test if the signal was present in the data without the use of inputs from the photometry, as a test of signal independence, we employed six chains with different temperature values ($\beta = 1.0, 0.6, 0.4, 0.29, 0.19$ and 0.13). The chain length was set to 15,000 steps and each chain had 150 walkers in the ensemble, giving rise to a total chain length of 13.5 million steps. A burn-in of 7,500 steps was also
used. A first-order moving average correlated noise model was used to model the high-frequency noise in the velocity data set, and the priors were set to be the standard priors as explained in the EMPEROR manuscript and on the GitHub page2. In automatic mode, EMPEROR detects the planet’s orbital signature with a Bayes Factor value of 5, highly significant, in the combined FEROS+CORALIE data, confirming the existence of the planet. The best fit made by EMPEROR is shown in Figure 6 and the phase folded curve in Figure 7. No additional signal was detected. The best fitting model from EMPEROR with respective uncertainties were used as Gaussian priors to determine a global model for this system.

2 https://github.com/ReddTea/astroEMPEROR

4.2 Global Modeling

For the global joint photometry and radial velocity modeling we used Juliet (Espinoza et al. 2018). Juliet is a python tool capable of analysis of transits, radial velocities, or both. It allows the analysis of multiple photometry and radial velocity instruments at the same time using Nested Sampling, Importance Nested Sampling, and Dynamic Nested Sampling algorithms. For the transit models, Juliet uses BATMAN (Kreidberg 2015), which has flexible options, in particular for limb-darkening laws. The Keplerian signal model is provided by radvel (Fulton et al. 2018). Finally for our Juliet run, given the high dimensionality of the model (29 free parameters between two radial velocity and four photometry instruments) we used Dynesty for Dynamic Nested Sampling as it has proven to be more efficient than regular Nested Sampling under these conditions.

The radial-velocity fit made by EMPEROR shows a low eccentricity orbit \( e < 0.01 \) thus for the Juliet modeling we decided to fix the eccentricity to 0. Since we have 213,549 NGTS photometry datapoints plus SAAO photometry in the \( V \) and \( I \) bands and TESS photometry, fitting such a large light curve is resource intensive, so we first binned the NGTS data in 10 minute cadence bins and then performed the fit with the binned data, supersampling the model light curve to 10 minute exposure times with 30 points in each bin. For the limb darkening we assumed a quadratic law for NGTS and TESS photometry, and a linear law for both SAAO bands. The parameters for the best fit are presented in Table 4 and in Figure 8 we show a corner plot with the main planetary parameters.

The light curves showcased in Section 2.3 show a clear \( V \) shape transit, suggesting the system is in fact, grazing. This introduces a strong degeneracy between the planet-to-star radius ratio and impact parameter and can produce extreme results (such as an extremely inflated planet). In order to
address this issue, a prior for the stellar density was used within Juliet, which allowed us to better decorrelate those two parameters and thus get more realistic results for the parameters of the planet.

5 DISCUSSION AND CONCLUSION

We report the discovery of NGTS-6b, a grazing transit UHJ with a period of 21.17 hours, mass of $1.330^{+0.024}_{-0.028}M_J$ and radius of $1.271^{+0.197}_{-0.188}R_J$, and the first UHJ from the NGTS. We analyzed the joint photometry and radial velocity data using Juliet, testing its modeling abilities when given a likely grazing transit. There are only a handful of USP planets in the literature, of which only six are giant plan-

Table 4. Planetary Properties for NGTS-6b

| Property | Value |
|----------|-------|
| P (days) | 0.882058 ± 0.000001 |
| T_C (BJD - 2450000) | 7982.3785 ± 0.0003 |
| a/R_s | 5.447 ± 0.037 |
| b | 0.933^{+0.036}_{-0.034} |
| K (km s^{-1}) | 0.322^{+0.006}_{-0.007} |
| e | 0.0 (fixed) |
| M_p (M_J) | 1.330^{+0.024}_{-0.028} |
| R_p (R_J) | 1.271^{+0.197}_{-0.188} |
| \rho_p (g cm^{-3}) | 0.805^{+0.498}_{-0.283} |
| a (AU) | 0.016623018 ± 9.84 x 10^{-9} |
| inc (deg) | 80.231^{+0.358}_{-0.385} |

Figure 8. Juliet posterior distributions for the main planetary parameters. The red dashed lines are the median of each distribution and the dash-dot lines represent the 1σ confidence interval. A correlation between the impact parameter and the planet to star radius is expected due to the grazing nature of the system.

Figure 9. Planetary radius against orbital period. Plotted are all USP planets and UHJs from the well-studied transiting planets catalog that have both measured mass and radius. The dark contours and purple shading highlight the planet number density of the sample. The green pentagon shows the position of NGTS-6b.

Figure 10. Similar to Figure 9 except we show the planet bulk density against orbital period.

Figure 11. Similar to Figures 9 and 10 except here we show the planet mass against planet radius.
the ratio of the X-ray and bolometric luminosities, \( L_X/L_{bol} \), with stellar age. Using the CORALIE-derived age of 9.6 Gyr yields an estimate of \( L_X/L_{bol} = 1.0 \times 10^{-5} \) at the current epoch. This corresponds to an X-ray luminosity \( L_X \approx 6 \times 10^{27} \text{erg s}^{-1} \), or a flux at Earth of \( 5 \times 10^{-16} \text{erg s}^{-1} \text{cm}^{-2} \). Such a flux would require a very deep observation with current generation X-ray telescopes in order to detect the star. Using the energy-limited method of estimating atmospheric mass loss (Watson et al. 1981; Erkaev et al. 2007), our estimate of \( L_X \) yields a mass loss rate of \( 1 \times 10^{11} \text{g s}^{-1} \). By integrating the mass loss rate across the lifetime of the star (following the X-ray evolution described by Jackson et al. 2012) we estimate a total mass loss of about 5 per cent. This is not enough to have significantly evolved the planet, in line with theoretical studies of HJs (e.g. Murray-Clay et al. 2009; Owen & Jackson 2012).

We found the host star to be metal-rich, with a value for the iron abundance [Fe/H] of +0.11±0.09 dex. It is well established that gas giant planets favour metal-rich stars (Gonzalez 1997; Santos et al. 2002; Fischer & Valenti 2005; Wang & Fischer 2015), and also short period gas giants, including the HJ population, also appear even more metal-enhanced when compared to their longer period cousins (Jenkins et al. 2017; Maldonado et al. 2018). This trend appears to continue into the USP planet population also (Winn et al. 2017). Approximately 50% of the UHJ planets host stars are found to have super-solar metallicities ([Fe/H]≥ +0.1 dex), whereas for the smaller super-Earth population, only 30% orbit such stars. Since the UHJ sample is still significantly smaller than the super-Earth sample, NGTS-6b adds statistical weight to this finding, and the conclusion that this points towards is that both these populations form through core accretion processes (Matsuo et al. 2007), with the HJ sample forming at relatively large separations from their host stars, and later migrating inwards either through disk driven migration (Mandell et al. 2007; Terquem 2014) or high-eccentricity processes like planet-planet scattering (Rasio & Ford 1996; Ford et al. 2001; Papaloizou & Terquem 2001; Ford & Rasio 2008).

One way to place further statistical constraints on the evolutionary mechanism that brought NGTS-6b in so close to its host star would be to collect more radial-velocity observations. This would not only better constrain the orbital solution of the planet, but it would also allow the search for additional longer period companions to be made. Finding additional companions in the system may point to a planet-planet scattering origin for NGTS-6b (Petrovich et al. 2018). Most USP planets are associated with longer period companions (Sanchis-Ojeda et al. 2014; Adams et al. 2017; Winn et al. 2018), where 52%±5% of HJs have additional, longer period companions (Bryan et al. 2016), and therefore we may expect these types of planets to be part of multi-planet systems.

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