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NGTS — Uncovering New Worlds with Ultra-Precise Photometry

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The Next Generation Transit Survey (NGTS) is a state-of-the-art photometric facility located at ESO's Paranal Observatory. NGTS is able to reach a precision of 150 ppm in 30 minutes, making it the most precise ground-based photometric system in the world. This precision has led to the discovery of a rare exoplanet in the "Neptune Desert" (NGTS-4b), the shortest-period hot Jupiter ever discovered (NGTS-10b), and the first exoplanet recovered from a TESS monotransit candidate (NGTS-11b). It has also allowed NGTS to characterise exoplanet candidates transiting very bright stars ($V < 10$) from the TESS mission, and to make coordinated observations in support of VLT programmes.

Exploring other worlds

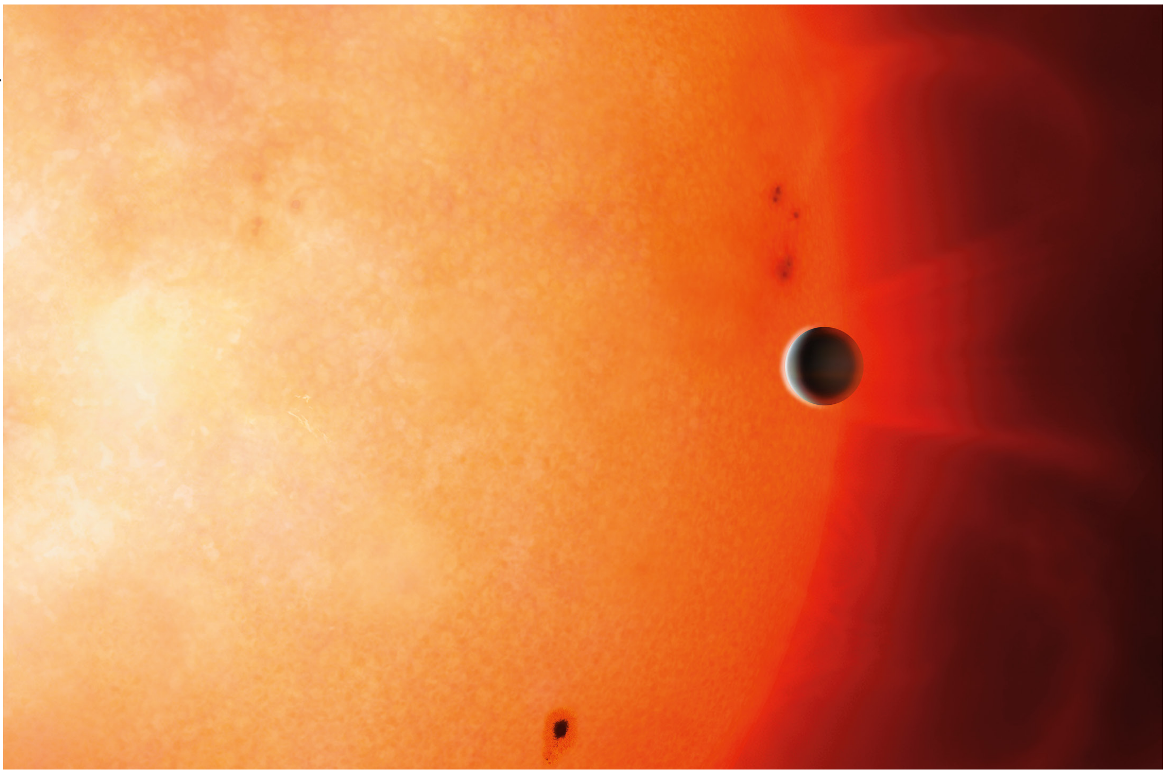
It has been a quarter of a century since the ground-breaking discovery of 51 Peg b (Mayor & Queloz, 1995) brought the field of exoplanet research to life. As we continue to discover exoplanets in ever greater numbers, the challenge is now to try to understand the astounding diversity of these worlds, many of which have no analogues in our own Solar System. The Next Generation Transit Survey[1] (NGTS; Wheatley et al., 2018) is at the forefront of this effort, finding and characterising transiting exoplanets around bright stars.

The NGTS facility

The NGTS facility is a set of twelve fully robotic and automated 20-cm telescopes located at the Paranal Observatory in Chile (see Figure 1). Housed in a single roll-off roof enclosure just under 2 km from the VLT, NGTS was built at Paranal Observatory to take advantage of the site's excellent photometric conditions. All aspects of the NGTS design, from the ultra-stable telescope mounts to the high-quality CCD cameras, were tailored to ensure NGTS would deliver the highest possible photometric precision. Such precision is needed to detect the tell-tale dip in a star's brightness caused by an exoplanet passing in front of it. NGTS is sensitive to detecting dips of just 0.1%, which equates to a Neptune-sized planet transiting a Sun-like star.

NGTS began science observations in April 2016 (West et al., 2016) and for

Figure 1. The twelve NGTS telescopes at dusk, just about to begin nighttime operations. The NGTS facility is located at ESO's Paranal Observatory in Chile. The VLT can been seen in the background.



M. Garlick & University of Warwick

Figure 2. Artist's impression of NGTS-4b, a Neptune-sized exoplanet in the "forbidden" zone around its host star.

the past four years NGTS has been surveying the southern skies for transiting exoplanets around bright stars. In this article we highlight some of the key discoveries from NGTS and outline the exciting future we envisage for exoplanet science with NGTS.

The "forbidden" planet — NGTS-4b

The high photometric precision of the NGTS facility has allowed us to discover rare objects that were not visible to previous ground-based exoplanet surveys. One such example is NGTS-4b, a Neptune-sized planet orbiting a bright K-dwarf star (West et al., 2019; see Figure 2). The transit of NGTS-4b is just 0.13% deep, far shallower than that of any planet previously discovered from ground-based photometry. This breakthrough demonstrates the ability of NGTS to discover exoplanets that present only very shallow transits in our time-series photometry.

NGTS-4b orbits its host star in just 1.34 days and is thus subject to relatively strong irradiation. Previously, the Kepler survey (Borucki et al., 2010) revealed that Neptune-mass planets are not found this close to their host stars (Mazeh, Holczer & Faigler, 2016), the region being called the "Neptune Desert". The likely cause of the lack of short-period Neptune-mass planets is that these planets are not massive enough to retain their H/He atmosphere in such a high-radiation environment. So, over time, they would evaporate away to become the much smaller "super-Earth" planets that are found in great abundance by Kepler.

However, NGTS-4b does not fit this picture. Radial velocity measurements made using the High Accuracy Radial velocity Planet Searcher (HARPS) instrument on the ESO 3.6-m telescope reveal that the mass of NGTS-4b is just 20 $M_{\oplus}$, so we would not expect it to be able to retain its

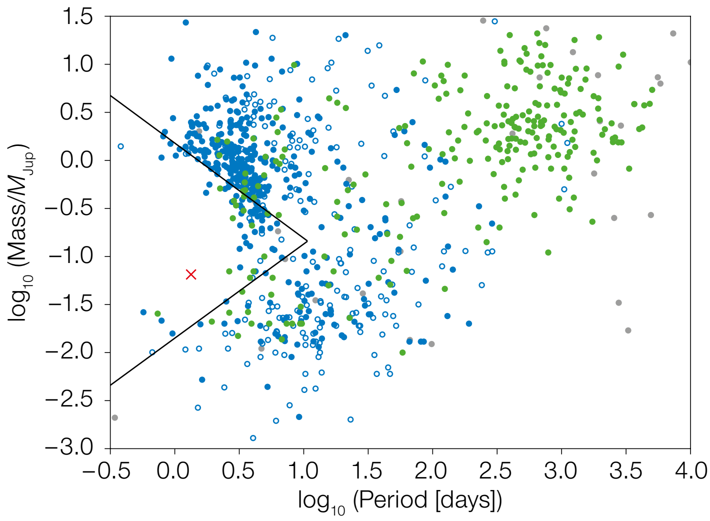


Figure 3. The distribution of exoplanet masses and orbital periods, showing a dearth of Neptune-mass planets in short-period orbits. The "Neptune Desert" is the region interior to the solid black lines. Exoplanets are colour-coded by discovery method: transit (blue), radial velocity (green) and other methods (grey). Exoplanets with masses measured to better than 30% are represented as filled circles. NGTS-4b (red cross) stands out as being well inside the Neptune Desert. Figure from West et al., 2019.

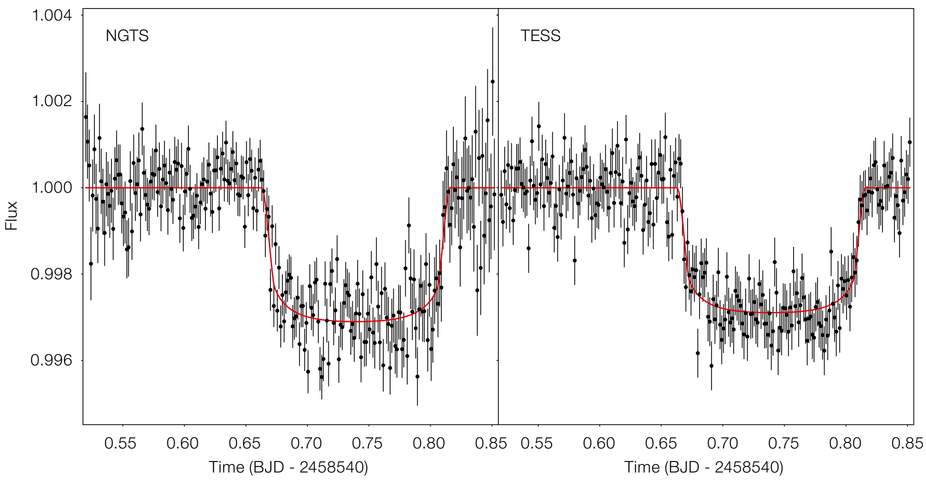


Figure 4. The transit of WASP-166b on the night of 25 February 2019. The data on the left are from the combination of nine NGTS telescopes (binned to two minutes). The data on the right are the TESS space telescope observation of the same transit event at a two-minute cadence. The red line is a best-fit transit model to the data. NGTS achieved an average photometric precision of 150 ppm across the transit event — a similar precision to that of TESS. Figure from Bryant et al., 2020.

atmosphere so close to its host star. It lies almost in the middle of the Neptune Desert — a "forbidden" planet! (see Figure 3). Given that there is no indication that NGTS-4 is a particularly young star, it is surprising to find an exoplanet like NGTS-4b, and its existence presents an opportunity to unravel the processes that control planetary evaporation.

The shortest-period hot Jupiter ever found: NGTS10b

Another rare planet that NGTS has recently uncovered is the ultra-short-period NGTS-10b (McCormac et al., 2020). Incredibly, NGTS-10b orbits its host star in just 18 hours, making it the shortest-period gas giant planet ever found. Being this close to its host star, NGTS-10b is expected to be undergoing rapid inspiral as a result of tidal orbital decay. The predicted lifetime of NGTS-10b is just 40 Myr, making it a very fortuitous find indeed. The predicted inspiral rate is estimated to be on the order of 7 seconds over a decade, which is potentially detectable. This inspiral rate is strongly dependent on the planet's tidal quality factor (Q_P), which is currently highly uncertain for giant exoplanets. We have initiated a long-term project on NGTS in order to try to measure tidal orbital decay on NGTS-10b and other ultra-short-period gas giants.

The discovery of NGTS-10b highlights two key advantages that NGTS holds over other transit surveys, such as NASA's Transiting Exoplanet Survey Satellite (TESS). Firstly, NGTS imaging is carried out at a very high time cadence — approximately 13 seconds per image. This allows us to fully resolve the transit event, even for systems like NGTS-10b where the transit is just one hour in duration. Such events are not well resolved with the 30-minute cadence of Kepler or TESS full-frame imaging. Secondly, the spatial scale of the NGTS imaging is four times finer than that of TESS, allowing us to resolve many neighbouring stars that would be blended in TESS imaging. NGTS-10 happens to be located just 40 arcseconds from a very bright star (V = 9.32), which would result in highly blended photometry in most other wide-field transit surveys.

The first discovery from a TESS monotransit: NGTS-11b

One of the primary limitations of using the transit method to discover exoplanets is that it is extremely biased towards finding very short-period exoplanets. This potentially leaves a wealth of longer-period planets hidden. Crucially, the longer-period planets that most transit surveys miss include planets in the so-called "habitable" zone of the host star — the zone within which liquid water could exist on the surface of an exoplanet. We are therefore eager to extend the reach of transiting planet surveys towards these longer-period planets, and the NGTS team is doing this via "monotransits" from the TESS mission.

A monotransit occurs when only a single transit is present in the duration of the photometric monitoring of a star. Monotransits are common in the TESS data, since most stars are only monitored for approximately 27 days. Simulations show that we can expect over 1000 monotransit events from a single year of TESS data (Cooke et al., 2018). However, there are two large stumbling blocks when working with these monotransits. First, with only a single event in the photometric data, the chance that the signal is a false alarm is far higher than normal. Second, even if the event is a real astrophysical signal, with only a single transit we cannot determine the orbital period of the planet or predict the next transit. It is therefore extremely difficult to discover transiting planets based on monotransits in the TESS data.

To overcome these difficulties, the NGTS team has set up a project to carefully sift through the TESS lightcurves to detect monotransits, and then to schedule the candidates on to individual NGTS telescopes for further monitoring. We focus on TESS monotransit candidates from giant planets transiting bright stars. This project fits in well to our regular NGTS monitoring programme, the only difference being that field positions are selected to include the TESS monotransit candidates.

Our first three successful recoveries were TOI-222 (Lendl et al., 2020), TIC-238855958 (Gill et al., 2020a) and TIC-231005575 (Gill et al., 2020b) with periods of 33.9 days, 38.2 days, and 61.8 days, respectively. In all cases radial velocity measurements revealed that, although the transiting objects were similar in size to gas giant exoplanets, they were actually very low-mass stars (0.1 to 0.2 $M_{\odot}$). These very low-mass stars are interesting in their own right, as precise masses and radii have been measured for only a handful of such stars. These discoveries complement the NGTS studies into other low-mass star systems, such as our discoveries of low-mass companions to M-dwarf stars (Casewell et al., 2018; Acton et al., 2020).

On the night of 24 October 2019, after monitoring the field for 80 nights, NGTS detected another transit around a TESS monotransit candidate. The detected transit matched the depth and duration of the TESS transit, but there was over a year between these two transit events. This left us with a set of 13 possible periods for the system. Radial velocity measurements from HARPS on the ESO 3.6-m telescope revealed that the true orbital period was 35.5 days, and that this time NGTS had detected an exoplanet, named NGTS-11b, with a mass of 0.34 M_{Jup} (Gill et al., 2020c). NGTS-11b is the first exoplanet to be discovered from a TESS monotransit event!

With an orbital period of 35.5 days, NGTS-11b is a transiting giant planet with one of the longest periods found to date. The equilibrium temperature of NGTS-11b is just 435 K, and it therefore presents an opportunity for future atmospheric transmission spectroscopy with the wide range of ESO instrumentation able to probe an exoplanet atmosphere much cooler than those of typical transiting gas giants (> 1000 K). Figure 5 shows the irradiating flux received by NGTS-11b compared with other transiting planets, demonstrating the unique nature of this exoplanet.

Many telescopes make light work

In typical survey mode, the NGTS telescopes each observe a different area of the sky searching for transiting exoplanets. However, the design of NGTS makes it possible for several telescopes to simultaneously observe a single star. For bright stars ($V < 10$), where scintillation is the dominant source of photometric noise, this is especially beneficial since the scintillation noise is independent for each telescope. As a result, by combining multiple NGTS telescopes, we are able to increase our photometric precision. Early testing of this operation mode in 2017 was very promising, with a multi-telescope observation capturing the 0.1% transit of HD 106315c (Smith et al., 2020).

To further study the potential of this new mode of operation, we used nine NGTS telescopes to observe a transit of WASP-166b simultaneously with the TESS spacecraft. WASP-166 is a bright ($V = 9.3$) F-type dwarf star which hosts a transiting exoplanet in a 5.4-day orbit (Hellier et al., 2019). The exoplanet is very inflated — it is about twice the mass of Neptune but has a density less than half that of Jupiter. The transit is only 0.3% in depth, so presents a challenging target for ground-based facilities.

By combining nine NGTS telescopes, we were able to achieve a photometric precision of 150 parts per million (ppm) on a 30-minute timescale (Bryant et al., 2020). Such precision was previously the preserve of space-based photometry such as the TESS mission (Ricker et al., 2015). Since we observed the transit simultaneously with TESS, we are able to directly compare our lightcurve to the TESS lightcurve — which we show in Figure 4. NGTS reaches a precision similar to that of TESS for this target.

The power of using multiple NGTS telescopes in this coordinated manner is now being utilised to undertake critical photometric observations for discoveries of exoplanets around bright stars. Already, NGTS multi-telescope photometry has contributed to some of the most exciting discoveries from the TESS mission, for example, TOI-849b, the remnant core of a giant planet (Armstrong et al., 2020) and LTT 9779b, the most highly irradiated Neptune-mass planet ever discovered (Jenkins et al., 2020). NGTS is pleased to make lightcurves of bright TESS candidates available to the community through its membership in the TESS Follow-Up Program[2].

Data for the community

All of the NGTS data are made publicly available to the community via the ESO archive[3]. The first NGTS data release was in November 2018 and consisted of 24 separate fields (each 2.8 × 2.8 degrees) completed during the first year of observations (April 2016 to April 2017). The data release includes a catalogue of the observed sources down to $V = 16$, together with the lightcurves and full-frame images. The data release contains lightcurves for over 200 000 sources, and in total equates to around 32 billion data points at a 13-second cadence.

The next NGTS data release (DR2) has just been released[4] and includes all survey fields completed by NGTS up to April 2018. The data release contains over 600 000 lightcurves and approximately 13 million individual full-frame images.

With the advent of multi-telescope observations, NGTS is now able to provide

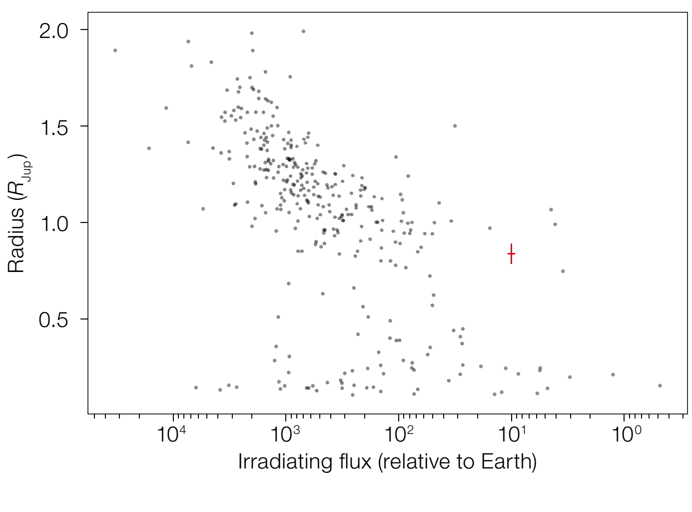


Figure 5. The irradiating flux for well characterised transiting planets (black circles) and NGTS-11b (red cross) in units of irradiation received by the Earth. NGTS-11b is one of the least irradiated transiting gas giant exoplanets known. Figure from Gill et al., (2020c).

photometry at a level of ~ 150 ppm for selected bright stars. Given that the NGTS telescopes are located at Paranal Observatory, we have also started coordinated photometric monitoring of stars to aid observations from instruments such as the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations (ESPRESSO) on the VLT. Figure 6 shows one such coordinated campaign, where NGTS monitored the star WASP-52 in order to measure the stellar activity to support ESPRESSO transit spectroscopy. NGTS welcomes collaborations with any VLT users who would find it useful to acquire coordinated high-precision photometry of their bright star targets.

In addition to exoplanet science, NGTS is making important contributions to stellar astrophysics, particularly with respect to young stars and stellar flares. As part of our young open cluster monitoring programme, we observed the Blanco 1 cluster over 200 days and determined rotation periods for 127 stars, which provided new insights into the angular momentum evolution of FGKM stars at approximately 100 Myr (Gillen et al., 2020). NGTS imaging is also being used to study stellar flares at a high time cadence, which has led to a number of important discoveries including the first detection of a white-light flare from an ultracool L2.5 dwarf star, an event which briefly caused the star to brighten by 6 magnitudes (Jackman et al., 2019).

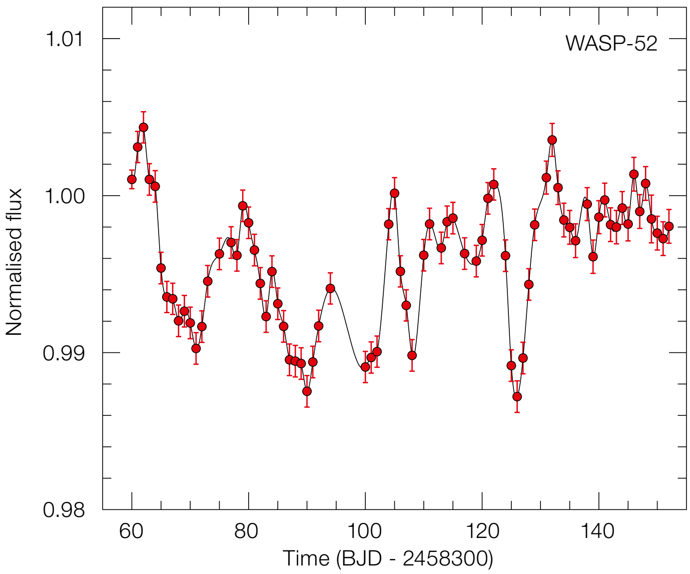


Figure 6. Long-term NGTS monitoring of WASP-52. The NGTS photometric points (red points) and a cubic spline (black solid line). The NGTS photometry is able to map out the spot activity for WASP-52, aiding in the interpretation of three spectroscopic transits of WASP-52b observed by ESPRESSO during this time period.

A bright future

NGTS has now been operating for over four years and is producing photometry for bright stars that is on a par with space-based photometry. Over the coming years, NGTS will be at the forefront of exoplanet discoveries for both bright planet-hosting stars and for longer-period transiting planets.

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Links

[1] NGTS Webpage: https://ngtransits.org/
[2] TESS Follow-Up Program: https://tess.mit.edu/followup/
[3] NGTS DR2: http://archive.eso.org/scienceportal/home
[4] Documentation: http://eso.org/rm/api/v1/public/releaseDescriptions/154