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Galactic panel
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Confirming hot and ultra-short period Saturns and Jupiters from the Next Generation Transit Survey

Abstract

The Next Generation Transit Survey (NGTS) is a ground-based wide-field transit survey, monitoring stars with I < 16. It obtains full-frame
images from twelve independent telescopes. The NGTS was designed with the aim of discovering Neptunes and Earth-size planets in
the southern hemisphere. We request two runs of 4 nights with the FEROS instrument on the 2.2-m ESO/MPG telescope at La Silla
Observatory to observe 10 stars from our vetted NGTS candidates that have radii commensurate with Saturn-Jupiter size objects derived from
the transit light curve and periods smaller than 10 days. Our radial-velocity follow-up has allowed us to confirm 25 new transiting
where FEROS proved to be key in constraining the orbits. In addition to confirming the planetary nature of our candidates, FEROS velocities
will also help constrain companion densities, allowing us to study bulk composition and formation mechanisms of the detected planets, and
their stellar interactions

Observing Blocks

Instrument/Telescope	Req. time	Min. time	1^{st} Option	2^{nd} Option
FEROS/MPG 2.2-m	4 nights	3 nights	October Any	November Any
FEROS/MPG 2.2-m	4 nights	3 nights	February Any	March Any

CoIs

Name	Institution	e-mail	Observer?
Douglas Rodrigues Alves	UCH	douglasalvesastro12@gmail.com	True
James Jenkins	UDP	james.jenkins@mail.udp.cl	False
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Maximilian Guenther	OnCL	maximilian.guenther@esa.int	False
Maximiliano Moyano	UCN	mmoyano@ucn.cl	False
Stephane Udry	OnCL	stephane.udry@unige.ch	False
Philipp Eigmuller	OnCL	philipp.eigmueller@dlr.de	False
David Anderson	OnCL	david.r.anderson@warwick.ac.uk	False

Status of the project

- Past nights: 41
- Future nights: 0
- Long term: False
- Large program: False
- Thesis: True

List of Targets

ID	RA	DEC	Mag
NOI-106557	07:11:20.0	-35:51:01.86	V=11.6
NOI-106619	01:10:46.2	-31:30:20.40	V=12.87
NOI-106755	09:07:33.6	-21:02:01.85	V=12.68
NOI-104499	05:53:07.9	-33:22:43.48	V=12.45
NOI-104264	20:54:45.6	-48:35:53.96	V=13.62
NOI-106555	07:15:17.2	-36:49:27.06	V=11.2
NOI-106097	09:06:53.8	-20:17:42.59	V=14.57
NOI-106310	13:45:00.0	-11:30:50.20	V=14.6
NOI-106617	05:21:41.1	-38:39:24.58	V=13.52
NOI-106332	17:40:34.6	04:57:58.35	V=14.48

SCIENTIFIC AIM AND RATIONALE

More than 5000 extrasolar planets have been detected to date and ground and space based photometry surveys have allowed us to both further constrain the orbital properties and, most importantly, to characterize the bulk properties for hundreds of these systems over a wide range in the parameter space. However, an important population of hot short-period planets ($P \lesssim 10$ days) have emerged, through which we can test and study current planet formation and evolution theories. Furthermore, an even more extreme population of ultra-short period hot Jupiters ($P \lesssim 1$ day) is emerging, allowing us to also study star-planet tidal interactions and gather candidates for orbital period decay studies, a particularly starved area of study since only one planet, WASP-12, has shown evidence for orbital period variations (Patra et al, 2020).

The Next Generation Transit Survey: The Next Generation Transit Survey (NGTS, Wheatley et al. 2018) was designed and built with the primary aim of discovering Neptunes and Earth-size planets (1.2-6 $R_\oplus$) orbiting bright and nearby stars (V$\leq$13) in the southern hemisphere (Günther et al. 2017). NGTS consists of an array of twelve 20cm f/2.8 telescopes, robotically operated, at the ESO Paranal Observatory. Each telescope is capable of monitoring 8 deg^2 of the sky at a time, and its one-tenth of a pixel precision guiding over a full night, makes it the most precise ground-based survey currently operating. NGTS is able to detect transits with depths of up to 1-2 mmag on time-scales of 10 minutes. It is also capable of operating at a quick 10s cadence, allowing us to detect transit signatures of ultra-short period transiting planets, including two of the shortest period giant planets discovered (NGTS-6b, Vines J. et al. 2019; NGTS-10b, McCormac et al. 2020)

NGTS as a complement to TESS: The NGTS also acts as a complement to TESS (Ricker et al. 2015). Given the significant difference in pixel size ($5{\times}5''$ as opposed to TESS' $21{\times}21''$), NGTS is less affected by blending due to a background stars, allowing us to follow-up candidates in more crowded fields (e.g. NGTS-10b, McCormac et al. 2019), or detect blended eclipsing binary false-positives within the TESS Objects of Interest (e.g. TOI-164 which was shown to be a blended eclipsing binary by NGTS). In addition, the higher cadence of NGTS is an important factor in resolving and sampling transits from ultra-short period planets and Hot Jupiters which can be of the order of 1 hour (e.g. LTT9779 b; Jenkins et al 2020).

Project Aims: Ultra-short period systems provide a unique window into the interactions between planets and their host stars. Some examples of these interactions include the brown dwarf NGTS-7Ab which appears to show spin-orbit synchronicity (Fig. 1; Jackman et al., 2019) and NGTS-10b which is the shortest period Hot Jupiter (HJ) discovered to date, and is expected to show evidence of tidal decay in the following decade, allowing for further studies of its interior structure (Fig. 1; McCormac et al., 2020). Another example of an ultra-short period HJ is NGTS-6b, which is ideal for orbital decay follow up studies, thanks to its V-shape transit making it easy to calculate the time of transit center. FEROS observations were crucial for its orbital characterization (Fig 3; Vines et al., 2019). While significant work has been done on inflated Jupiters and the mechanisms that lead to large radii (e.g. Lopez & Fortney 2016, Thorngren & Fortney 2018), the opposite is true for the understanding of dense Jupiters. From a combination of bulk densities and thermal evolution models, bulk metallicities of planets can be determined. These bulk metallicities are needed to fine tune planet formation models (Mordasini et al., 2014, Thorngren et al., 2016). More discoveries are still necessary to uncover the secrets behind HJs, for example, a recent study has revealed that the metallicity of planets does not appear to correlate with the metallicity of the host star (Teske et al., 2019).

We request 2 runs of 4 nights with the FEROS instrument on the 2.2-m ESO/MPG telescope at La Silla Observatory, to observe and measure the masses of 10 stars from

our vetted NGTS short-period candidates, with radii commensurate with Saturn-Jupiter size objects. The spectra will also provide activity indicators for each candidate, and since it has been shown that stellar activity can produce a shift in the spectral lines that mimics radial velocity (RV) signals (Díaz et al., 2018), we will model the stellar activity to gain a more precise measurement of the planet properties. The need for FEROS over Coralie data is highilted in Fig. 2, where the RV measurements obtained with FEROS are key to constrain the orbital parameters of the system. FEROS spectra will also be used to compute the stellar properties of the system, by measuring the equivalent widths of specific atomic lines. From these values we will obtain the temperature, surface gravity, metallicity, micro and macro turbulence velocity, rotational velocity, mass, age of the star, and abundances for 11 other chemical elements (see Soto et al., 2018). This method has already been used on other NGTS planetary candidates, like NGTS-2b and NGTS-6b (Raynard et al., 2018; Vines et al., 2019)

The data we extract from these observations will form the basis of our studies of the population of nearby planets from Jupiter to super-Earth bodies, in a uniform and homogeneous way, allowing us to explore the transition stage from gaseous-like planets, to smaller ones with or without a thick gaseous envelope, and finally to terrestrial planets with compositions similar to the Earth. We will also provide a number of planetary candidates that will be used to perform detailed atmospheric studies by instruments on some of the largest ground-based telescopes, such as the VLT and the upcoming GMT and ELT. The NGTS data and the quantity of follow-up studies provides a great opportunity to detect exciting planetary candidates, allowing us to better constrain theories of formation and migration from giant to rocky planets. **In particular, thus far only one planet, WASP-12b, shows strong evidence for tidally driven orbital decay (see Yee et al, 2020; Bouma et al, 2020), therefore we aim to increase the yield of USP planets, building up the sample of worlds with decaying orbits, whilst also allowing further insights into star-planet magnetic interactions and photoevaporation processes.**

References:

Díaz, M. R. et al 2018, AJ, 155, 126; Günther, M. et al. 2017a, MNRAS, 465, 3379; Günther, M. et al. 2017b, MNRAS, 472, 295; Raynard, L. et al. 2018, MNRAS, 481, 4960; Soto, M. G. & Jenkins, J. S. 2018, A&A, 615, 76; Wheatley, P. et al. 2018, MNRAS, 475, 4476; Vines, J. I. et al. 2019, MNRAS, 489, 4125; Ricker et al. 2015, JATIS; McCormac et al. 2020, 493, 126; Costes et al. 2019, 491, 2834; Patra et al. 2020, 159, 150; Yee et al. 2020, 888, 5Y; Bouma et al. 2020 893L, 29B; Jenkins et al. 2020 4 1148J

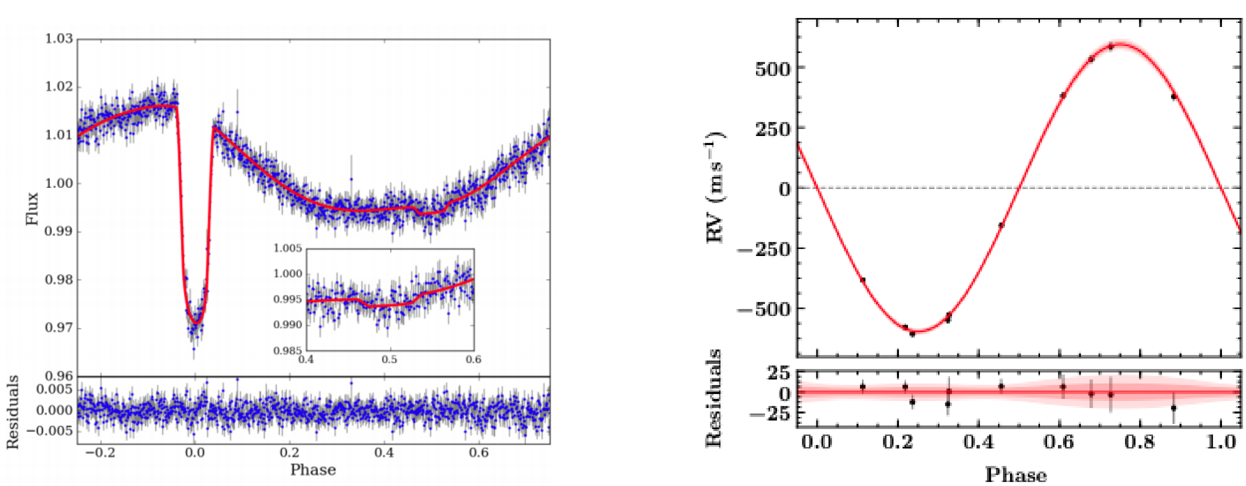

Figure 1: Left: NGTS-7Ab NGTS light curve. Right: NGTS-10b, the shortest period Hot Jupiter discovered to date.

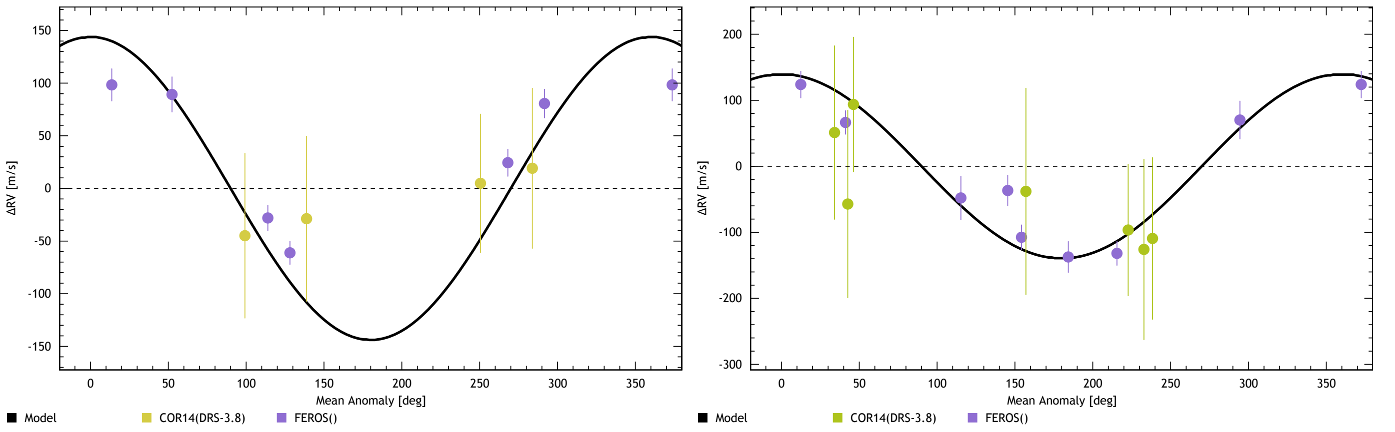

Figure 2: FEROS observations for (left) NOI-101195 and (right) NOI-103524 from our 2019A run. In both cases yellow points are Coralie observations and purple are FEROS. It is clear why FEROS is needed to recover the planets orbits. More observations are needed to fully constrain the orbits of these and many other NGTS targets which are not included in this plot to conserve space.

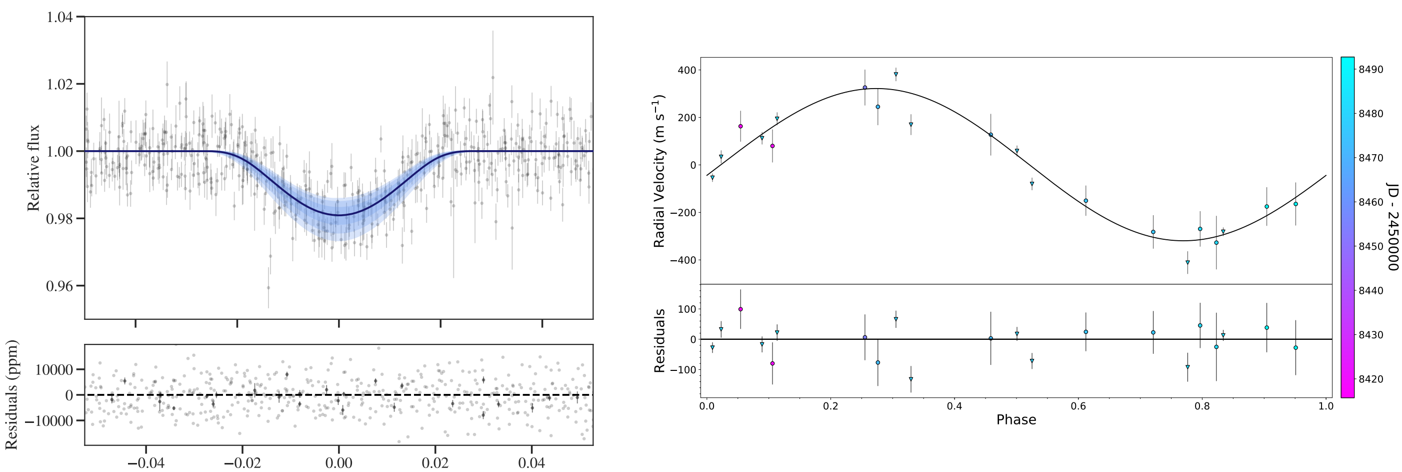

Figure 3: NGTS-6b transit light curve (left) from Vines et al. (2019), along with the simultaneously fit RV data (right). The blue and black solid curves and the blue shaded regions mark the best fit model and associated uncertainties, respectively. Upside down triangles are FEROS observations and circles are Coralie observations.

CURRENT STATUS OF THE PROJECT

NGTS targets have been extensively vetted through analyses including, but not limited to, odd/even numbered transits, centroiding shifts, ellipsoidal variation, and Coralie reconnaissance spectra (see Fig. 4 for examples), this has allowed us to vastly reduce the number of false-positives in our candidates, leading to increased efficiency during our follow-up campaign so far. In total we have 50 candidates awaiting RV confirmation, but since these are mainly between 13 and 15th magnitude, they can not be observed with Coralie, making them ideal for FEROS.

This project has already been awarded 41 nights in total from period 2016B to 2022A and are still awaiting observations from 2022A.

The previous data obtained with FEROS has been analysed by our team, showing promising results (Figures 2 and 3 in Scientific Rationale). We have also thus far been awarded time with the HARPS instrument in several periods. This time will be used to observe the Neptune and super-Earth size planetary candidates. Our RV follow-up data has allowed us to confirm 20 new transiting systems, including two ultra-short period Hot Jupiter discoveries, with one of these being the shortest period known to date (NGTS-6b, Vines J. et al. 2019; NGTS-10b, McCormac et al. 2019). **We also have 13 more planets that are being currently analysed, and 9 more candidates were identified during 2021A/B that show planetary RV signatures that require more observations from FEROS to fully confirm.**

FEROS observations are also key in maximizing the use of other instruments, as it allows us to forward candidates that show a "flat" RV signature in FEROS to them.

The student Vines is playing a major role in these discoveries, performing joint modeling of the transits and RVs using a Bayesian formulism with the EMPEROR.T code (Vines & Jenkins in prep), whilst also calculating the stellar parameters using ARIADNE[1] (Vines & Jenkins 2022)

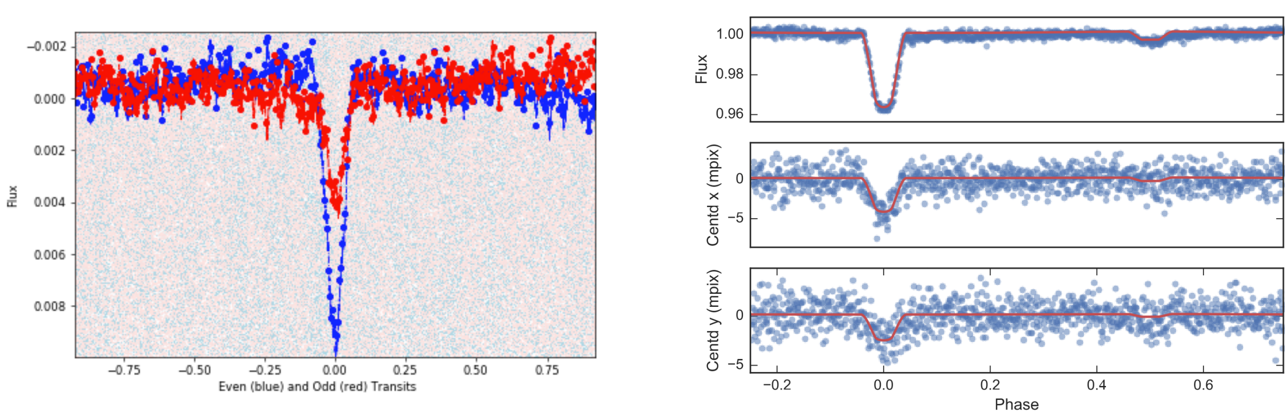

Figure 4: Example of two vetting diagnostics used in all possible candidates, before obtaining follow-up data. Left: Difference between odd and even numbered transits (Batalha et al. 2010). Right: Centroid shifting diagnostic from Günther et al. 2017b.

References:

Vines & Jenkins. 2022, MNRAS; Bayliss, D. et al. 2018, MNRAS, 475, 4467; Günther, M. et al. 2017, MNRAS, 472, 295; Wheatley, P. et al. 2018, MNRAS, 475, 4476; Vines, J. I. et al. 2019, MNRAS, 489, 4125; McCormac et al. 2019, 493, 126; Costes et al. 2019, 491, 2834; Jackman et al. 2019, MNRAS, 489; Teske et al. 2019, AJ, 158, 239; Lopez E. & Fortney J. 2016, ApJ, 818, 4L; Thorngren & Fortney 2018, AJ, 155, 214; Yee et al. 2020, ApJL, 888, L5; Bouma et al. 2020, ApJL, 893, L29

[1] https://github.com/jvines/astroARIADNE

TECHNICAL DESCRIPTION

We request 8 observing nights with the FEROS instrument during period 2022B to follow-up 10 stars with Jupiter and Saturn-sized planetary candidates from the NGTS project. We request two runs of 4 nights each, bracketed at the beginning and end of the semester so that we can access our full RA range from the NGTS fields we are following up. We note that we request a minimum of 6 nights that would be best scheduled as a single run in December 2022. Our targets have visual magnitudes $I \leq 12.5$, and the inferred planetary radii ranges from 0.5-2 R_J (assuming that $R_\star = R_\odot$). Planets with these sizes, orbiting stars with $M \sim M_\odot$ at periods $P \sim 4$ days (average period for the NGTS candidates), induce RV amplitudes from 50 to 120 m s^{-1} (assuming the evolutionary models from Fortney et al. 2007, and that planets with these orbital periods tend to be inflated). Our previous experience using FEROS (Soto et al. 2015, and our 2016-2019 runs) shows us that we can obtain a RV precision of ~ 10 ms^{-1}, when the signal-to-noise (S/N) of the spectra is of the order of ~ 45. This S/N is then enough for us to reach the desired precision that will allow us to detect the planetary candidates mentioned previously.

Our previous experience observing NGTS candidates with FEROS showed us that the most efficient way to reach a S/N$\sim$ 45 for targets with $I \sim 11.5$ is to have 30-minutes long exposures. Including overheads and any other delays, we should spend an average of 40 minutes per target. Assuming an 8h night, that would translate into 12 stars being observed per night. First off, for our new targets, our observing strategy consists of obtaining one spectra per star, to check for eclipsing binaries by looking for features in their CCFs, and active stars by measuring the $\log R_{HK}$ index (Noyes et al. 1984), allowing us to select RV stable targets. The majority of our sample are already known to be inactive and non-eclipsing binary systems through reconnaissance Coralie observations, and these will be monitored to confirm their planetary status and constrain their masses.

Experience through our previous campaigns on FEROS has taught us that a significant amount of time can be lost due to Target of Opportunity targets, sub-optimal weather conditions and different issues with the CCD that ultimately negatively affects data. We also need to observe a RV standard star each night, in order to correct for effects in the resulting RVs which could not be corrected by our pipeline. Taking all of these disruptions into account, we estimate that we will observe from 9 to 10 targets per night. In order to reach full-phase coverage for our confirmed candidates (after checking new targets for eclipsing binaries or active stars), we would expect to observe each vetted candidate at least 4 times during the run, once per night (assuming an average orbital period of 4 days). All of these factors lead us to request a total of 8 nights to obtain full phase coverage for at least 10 of the well vetted targets that are included in the target list for this program.

The data will be processed using the FEROS pipeline developed by Brahm et al. (2017), which performs the spectrum extraction, correction for the barycentric and nightly drift velocities (when using the simultaneous calibration lamp mode), computation of RVs by performing the cross-correlation function using a binary mask (available for G2, K5 and M2 spectral types), and measurement of activity indicators (bisector), allowing us to extract as much information as possible from each observation. We will also process the data independently using codes developed by our team for the computation of activity indices and stellar parameters, such that we can confirm all measured RVs. The pipeline also considers Moon contamination in the measurements of the RVs, allowing us to observe our candidates even in bright nights. Our targets won't be in close proximity to the Moon in any case, where we keep a minimum distance of 30^o between the target star and the Moon, further reducing the chance of contamination affecting our spectra.

References:

Brahm, R. et al. 2017, PASP, 129, 973; Fortney, J. J. et al. 2007, ApJ, 659, 1661; Noyes, R. W. et al. 1984, ApJ, 279, 763; Soto, M. G. et al. 2015, MNRAS, 451, 3131