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Galactic panel
Jose Vines | jose.vines.l@gmail.com
UCH
student

Confirming Warm Jupiters with TESS and the Next Generation Transit Survey

Abstract

Transiting exoplanets are a rich source of information and are revolutionizing our understanding of planetary formation and evolution. The known exoplanet population is strongly biased to close-in planets in short orbital periods (P $<$ 10d) but we cannot unravel the processes driving the formation and evolution of exoplanets using such a limited sample. TESS has brought a plethora of long-period planet candidates with a single transit feature, making follow-up efforts a long task. With NGTS we have been efficiently probing the true period of these candidates in order to select the most promising ones for spectroscopic follow-up. We request to observe 10 transiting planet candidates in orbits of tens to hundreds of days, which may well be part of a distinct population with its own formation and evolution history. For instance, the migration of close-in planets may be dominated by dynamical interactions, while disc migration may dominate for wider-separation planets.

Observing Blocks

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

CoIs

Name	Institution	e-mail	Observer?
James Jenkins	UDP	james.jenkins@mail.udp.cl	False
Maximiliano Moyano	UCN	mmoyano@ucn.cl	False
Douglas Rodrigues Alves	UCH	douglasalvesastro12@gmail.com	True
David Anderson	OnCL	david.r.anderson@warwick.ac.uk	False

Status of the project

- Past nights: 0

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

List of Targets

ID	RA	DEC	Mag
TIC-350432166	05:39:33	-59:00:21	11.9
TIC-358289302	04:08:42	-57:35:41	13
TIC-231281916	02:51:33	-52:03:57	13
TIC-229155120	01:54:21	-50:04:42	12
TIC-339399841	19:44:17	-62:48:49	13.1
TIC-262456555	15:14:49	-70:10:05	11
TIC-121077168	03:46:02	-19:03:03	14.4
TIC-25194908	04:15:37	-66:21:07	13
NGTS-11	01:34:05	-14:25:09	12.5
NOI-101822	05:48:10	-35:03:01	–

SCIENTIFIC AIM AND RATIONALE

More than 5000 extrasolar planets have been detected to date and ground and space based photometric 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, most of these planets are classified as hot Jupiters (HJ), having orbital periods of less than 10 days. While HJs prove to be invaluable laboratories for atmospheric studies, the original properties these systems had are not necessarily preserved, mainly due to different interactions with their host stars. Longer period planets ($10 < P \leq 200$), such as warm Jupiters (WJ), on the other hand, are far more rare, with only 10 planets falling in this regime.

Project Aims: WJs are systems that have been largely unaffected by their stellar host, and thus have their migration and formation history unaltered. This provides a unique opportunity to better understand planet formation and evolution through their atmospheres. In addition, planets with periods between 10 and 100 days are less frequent than their shorter and longer siblings. This paucity has been dubbed the period valley (Udry et al. 2003; Wittenmyer et al. 2010), and its existence suggests that there are different formation mechanisms at play, which in turn vary the occurrence rate of these objects. Another interesting feature of the WJ population is their wide eccentricity distribution, where two main groups are identified: the circular population and the eccentric population. While there are migration scenarios than can explain low eccentricity orbits (Baruteau et al. 2014), these fail to reproduce the high eccentricity population (Petrovich et al. 2014). On the other hand, high-eccentricity migration scenarios (Fabrycky & Tremaine 2007) do not produce an acceptable amount of low eccentricity planets (Wu & Lithwick 2011). To date, only a handful of WJs have their masses and radii determined better than 50% and 10% respectively (10 out of 789 planets with characterized masses and radii, see Figure 2), thus each new discovered WJ holds significant statistical importance for this population of planets.

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 ($5\times5''$ as opposed to TESS' $21\times21''$), NGTS is less affected by blending due to background stars, allowing us to follow-up candidates in more crowded fields (e.g. NGTS-10b, McCormac et al. 2020), 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). The orbital periods of WJs are such that during a single TESS sector there might be just one transit feature, making following up these targets a long and arduous task. NGTS allows for quicker orbital period recovery follow-up efforts without losing efficiency due to having 12 independent telescopes (e.g. Ulmer-Moll et al. 2022; Gill et al. 2020)

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 long-period candidates, with radii commensurate with 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. 3, 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 WJs, in a uniform and homogeneous way, allowing us to explore the period valley and the two different eccentricity populations. 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 of gas giant planets.

<u>**References:**</u>

Díaz, M. R. et al 2018, AJ, 155, 126; Günther, M. et al. 2017a, MNRAS, 465, 3379; 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; Jenkins et al. 2020 4 1148J; Ulmer-Moll, et al. 2022, A&A 666, 46; Gill et al. 2020, ApJ, 898, 11; Udry et al. 2003, A&A, 407, 369; Wittenmyer, R. A. et al. 2010, ApJ, 722, 1854; Baruteau, C. et al. 2014, Protostars and Planets VI, eds., 914, 667; Petrovich, C. et al. 2014, ApJ, 786, 101; Fabrycky, D., & Tremaine, S. 2007, ApJ, 669, 1298; Wu, Y., & Lithwick, Y. 2011, ApJ, 735, 109

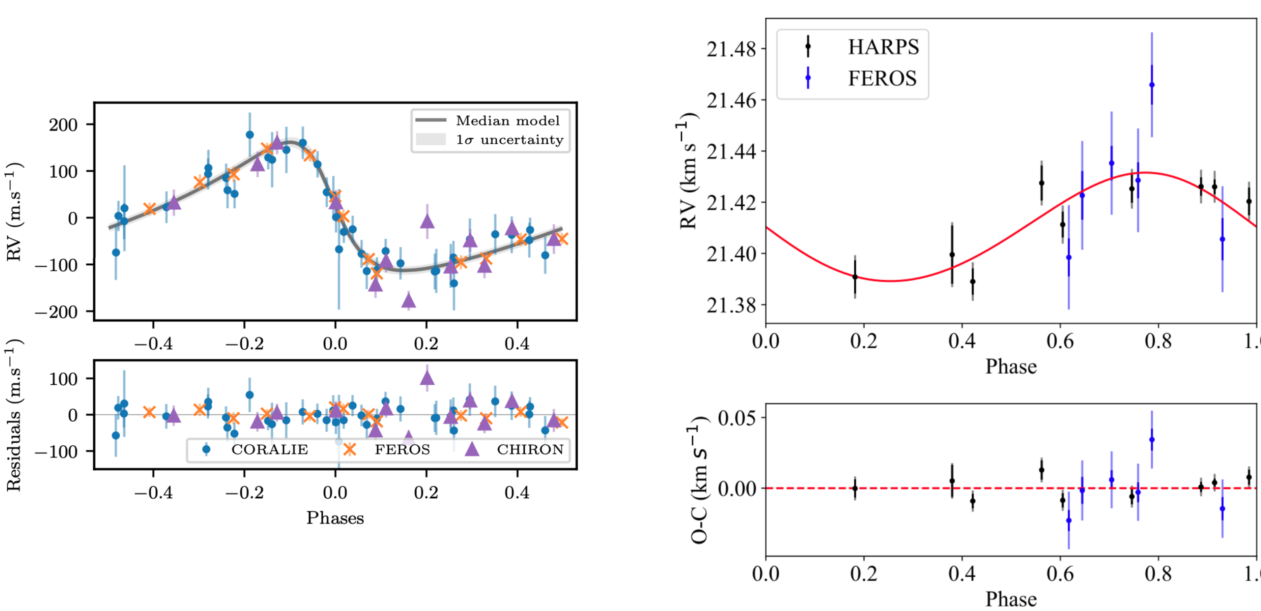

Figure 1: Phase folded RV plot for Left: NGTS-20b and Right: NGTS-11b. Two warm-Jupiters from NGTS

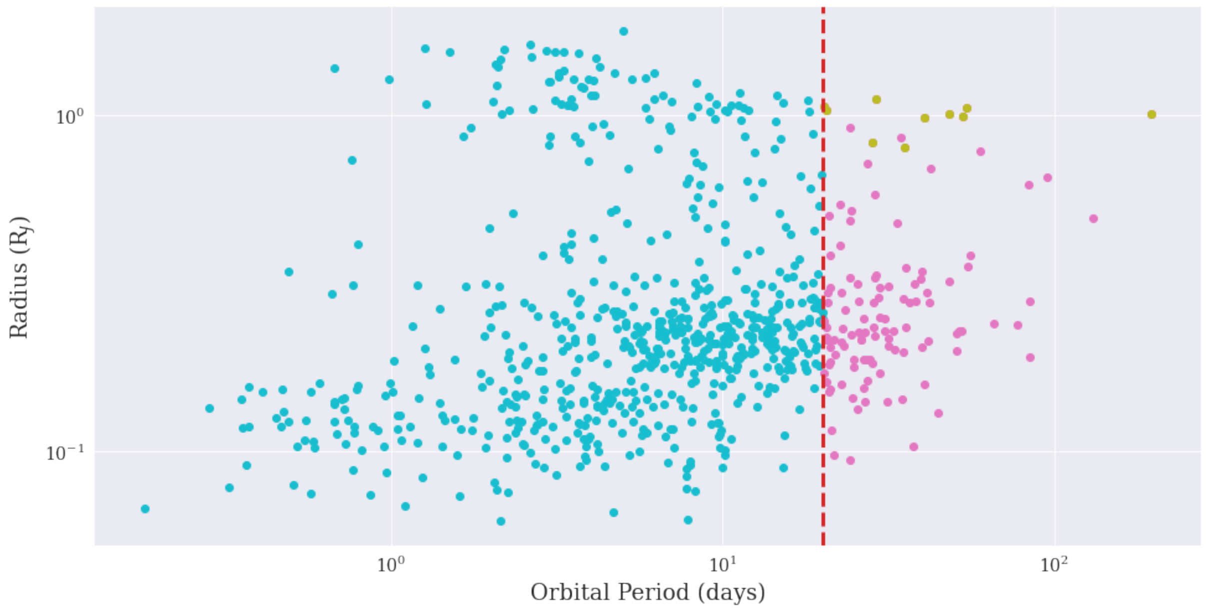

Figure 2: Radius-period diagram showing exoplanets discovered through the transit method. Teal points show planets with an orbital period less than 20 days, while pink points show the WJ population. Yellow points highlight WJs with masses and radii characterized to better than 50 and 10% respectively.

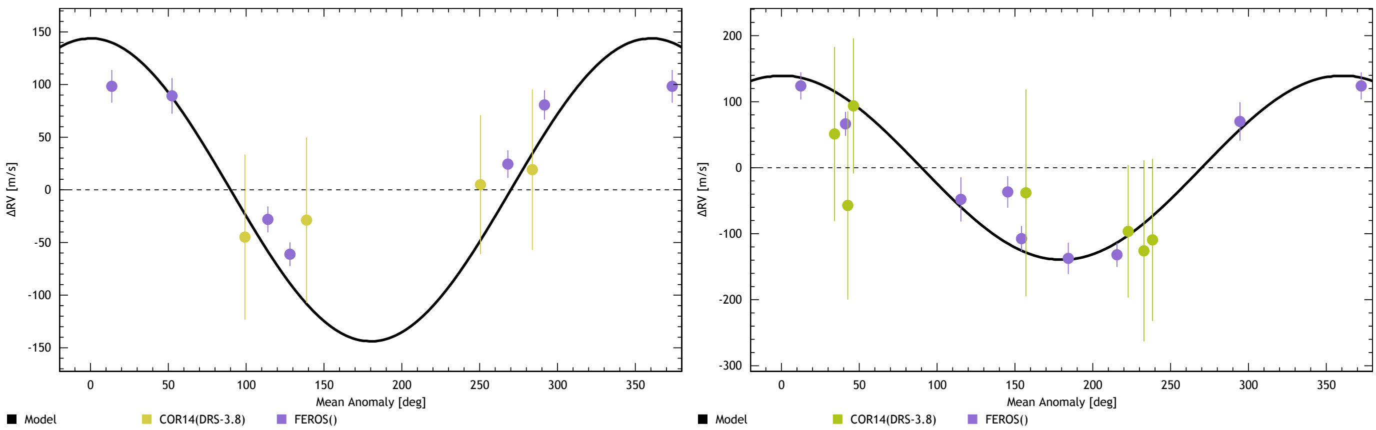

Figure 3: FEROS observations for (left) NOI-101195 and (right) NOI-103524 from our 2019A run. In both cases yellow points are Coralie observations and purple are FEROS. It is clear why FEROS is needed to recover the planets orbits. More observations are needed to fully constrain the orbits of these and many other NGTS targets which are not included in this plot to conserve space.

CURRENT STATUS OF THE PROJECT

As part of NGTS we have the monotransit working group, focused on vetting and validating monotransit candidates from TESS for photometric follow-up with NGTS. Early results from those efforts include three published WJs (NGTS-11, NGTS-20, TOI-5153; Gill et al. 2020; Ulmer-Moll et al. 2022) which used FEROS data for their publication (e.g. Figure 1 in the Scientific Rationale). We have more candidates currently being vetted as well. We have also thus far been awarded time with the HARPS instrument in several periods. This time will be used to further populate the long period orbits.

Previous NGTS RV follow-up campaigns have proven to be productive, allowing us to confirm 22 new transiting systems.

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)

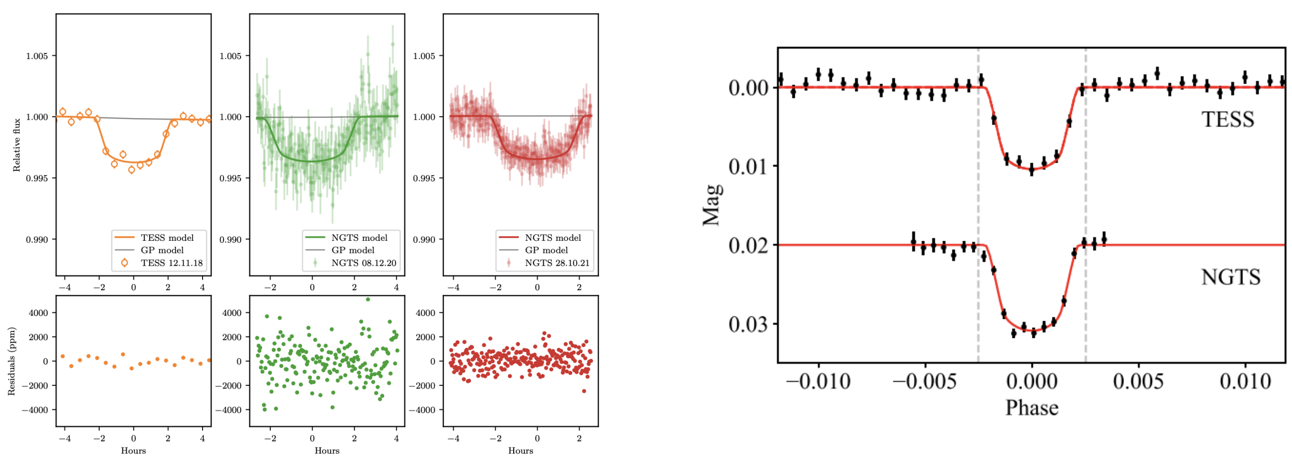

Figure 4: Example of two WJs with a single transit on TESS with photometric follow-up with NGTS that aided in recovering the true period. Left: NGTS-20. Right: NGTS-11

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; 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; Ulmer-Moll, et al. 2022, A&A 666, 46; Ulmer-Moll, et al. 2022, A&A 666, 46; Gill et al. 2020, ApJ, 898, 11

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

TECHNICAL DESCRIPTION

We request 8 observing nights with the FEROS instrument during period 2023A to follow-up XXX stars that have Jupiter-sized transits in TESS and have been vetted by NGTS. 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 of targets we are following up. We note that we request a minimum of 6 nights that would be best scheduled as a single run in June 2023. Our targets have visual magnitudes $I \leq 12.5$, and the inferred planetary radii ranges from 0.5-2 R_J (assuming that $R_\star = R_\odot$).

Our previous experience using FEROS (Soto et al. 2015, and our 2016-2022 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