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CN2020A-7

Galactic panel
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Doppler Tomography of a TESS warm Jupiter candidate

Abstract

The measurement of the angle between the stellar spin and the orbital plane of an exoplanet is a tracer of the orbital evolution of the planet. High eccentricity migration scenarios for close-in giant planets predict that an important fraction of warm Jupiters (WJs, particularly those having eccentric orbits) should present a wide diversity of spin-orbit angles. Nontheless, this prediction has not been easy to proove up to now due to the small fraction of warm Jupiters that happen to transit their parent stars. TESS is now efficiently discoverying this type of systems and we propose to measure the obliquity of a TESS WJ candidate. The high rotational velocity of the star coupled to its brightness makes of this system a suitable object to be analysed with the doppler tomography technique. We propose to spectrocopically observe with FEROS the two partial transits of this system that will occur in period 2020A, in order to confirm its planetary nature and measure its obliquity.

Observing Blocks

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

CoIs

Name	Institution	e-mail	Observer?
Andres Jordan	UAI	andres.jordan@uai.cl	False
Felipe Rojas	PUC	firojas@uc.cl	True
Pascal Torres	PUC	pjtorres1@uc.cl	True

Status of the project

- Past nights: 0
- Future nights: 0

- Long term: False
- Large program: False
- Thesis: False

List of Targets

ID	RA	DEC	Mag
TIC290403522	22:03:49.93	-72:26:26.99	V=10.787
TIC290403522	22:03:49.93	-72:26:26.99	V=10.787

SCIENTIFIC AIM AND RATIONALE

Scientific Context – The discovery of the first extrasolar planet orbiting a solar type star more than twenty years ago (Mayor & Queloz 1995, Nat 378, 355) was the milestone that boosted the creation of one of the most active current fields in astronomy. While this discovery was crucial to now know that the formation of planetary systems is a common outcome of the stellar formation process, its properties brought more questions than solutions with regarding the formation mechanisms of planets. 51 Peg b was afterwards termed as a hot Jupiter, a giant planet orbiting at extremely close separation from its parent star. Standard formation mechanisms of giant planets (Pollack 1996, Icarus, 124, 62) predict that there should be not enough material in the original protoplanetary disk to form the required massive cores. Nowadays, hot Jupiters are among the most studied population of exoplanets (see Dawson & Johnson 2018, ARA&A, 56, 175, for a comprehensive review). We know that this type of system is present in $\approx$1% of solar type stars, and that they tend to be found alone, with no additional planets at relatively short orbital distances. Nonetheless, the main question of how they can be found orbiting so close to their parent stars is still an unsolved theoretical challenge.

Some theorists have gone so far as to say that giant planets can actually form very close to their star (Batygin+2016, ApJ, 829, 114). However, most researchers maintain that giant planets form at large distances, and somehow lose orbital energy and angular momentum. Most of the proposed processes involve (1) transfer of energy and angular momentum to the protoplanetary disc (Lin+1996, Nat, 380, 606), or (2) exchange of angular momentum with other orbiting bodies, followed by energy loss through star-planet tides (Wu+2007, ApJ, 670, 820). It has not been possible to determine conclusively whether one or both of these mechanisms are operative, and if so, how often. There is good evidence, and a strong theoretical presumption, that orbital eccentricities of hot Jupiters have been altered by tidal interactions. There is also suggestive evidence for orbital decay, and the damping of any orbital mis-alignments relative to the stellar equatorial plane that could have been present after migration (Dawson 2014, ApJL, 790, 31). These effects tend to erase any clues about the previous orbital evolution, and thereby confound the theoretical interpretation. The best way forward is to improve our knowledge of "warm Jupiters," defined as giant planets with orbital semi-major axes in the range 0.1-1 AU, i.e., too close to form in-situ according to standard core accretion, and too far for significant tidal effects. Doppler surveys have taught us that warm Jupiters have a broad range of orbital eccentricities, with most of them exceeding 0.2. At face value, this finding implies gravitational interactions between massive bodies, but there remain theoretical problems with that interpretation. Namely, planet-planet interactions in close orbits are expected to result mainly in collisions rather than eccentricity excitation (Petrovich+2014, ApJ, 786, 101).

One proposed mechanism that can account for both hot Jupiters and eccentric warm Jupiters is high-eccentricity tidal migration through secular gravitational interactions with a third body (Kozai 1962, AJ, 67, 591). This scenario invokes a star or planet on a wider orbit that is eccentric, inclined, or both. The gravitational perturbations from this third body cause long-term cyclic variations in the orbital eccentricity and inclination of the inner planet, ultimately shrinking the periastron distance enough for tidal forces to shrink the orbit. Tidal migration begins when the orbital eccentricity approaches unity, but because tidal evolution is initially very rapid, the planet spends most of the time on a moderately eccentric orbit. The secular periods are too long to be directly observable, but the theory does make a testable prediction: many warm Jupiters should be found on orbits that are highly inclined with respect to the stellar spin axis (Dong+2014, ApJL, 781, 5).

Spin-orbit angles can be determined for transiting planets by analysing the changes of the spectral line profile of the star during a transit. As the planet transits along the disc of the star, it blocks regions with different projected radial velocity component due to the rotation of the star. If the planet has a pro-grade orbit with respect to the stellar spin, it will first block regions of the star that are approaching to the observer (blue zones of the spectral lines), and then it will block regions of the stellar disc residing from the observer (red zones of the spectral lines). In the case of a retrograde orbit, the opposite phenomena will occur. An accurate modeling of this effect can be used to measure the projected spin-orbit angle (obliquity). In the case of stars with moderate rotations (vsini< 15 km/s) this can be done through the measurement of the Rossitter-McLaughlin (R-M) effect , which corresponds to the characterization of an anomalous radial velocity signal during transit produced by the aforementioned mechanism. For stars with greater rotational velocities, the R-M effect cannot be directly used because the precision of the RV measurements significantly worsens, where the RV errors become larger than the amplitude of the R-M effect. In this case, though, the doppler tomography (DT) technique has been successfully applied for to determining the obliquity of several hot Jupiters. This technique consists in measuring the rotational profile of the star through a de-convolution between the observed spectra and a synthetic template, and then identify the shadow generated by the planet on top of this profile during transit.

While spin-orbit angles have been measured successfully for dozens of hot Jupiters (e.g. Triaud+2010, A&A, 524,25), this parameter has been obtained only for a handful of giant planets with periods longer than 10 days. This is due to the small fraction of discovered warm Jupiters that transit their host stars, the small number of transiting warm Jupiters having host stars bright enough to allow this type of observations, and the small number of transit opportunities per system if compared to hot Jupiters. However, as was stressed in the previous paragraphs, the determination of the spin-orbit angles of warm Jupiters is key for understanding how is the migration mechanism of giant planets.

Specific Objective – In the context of a Chilean-based collaboration aiming at discovering new transiting warm Jupiters by combining data from the Transiting Exoplanet Survey Satellite (TESS) and ground based facilities, we have identified a strong warm Jupiter candidate orbiting the star TIC290403522 (see Figure 2). It was identified from the light curves generated from our Full Frame Images pipeline (Rojas et al in prep, co-I). We identified the candidate first as a single transiter from sector 1, but it was observed again in the last sector of the southern hemisphere (sector 13) where we found 2 additional transits. The candidate has a period of 22.4 days, a predicted radius of R_P=1.1R_J, and orbits a bright (V=10.8) F-type star. We have obtained 18 FEROS RVs which show that the host star presents a relatively high rotational velocity (vsini=45 km/s), which significantly limits the precision of our RV measurements. Our current upper limit on the semi-amplitude of the keplerian signal is of 400 m/s. While the confirmation of this system using RVs is challenging, TIC290403522 is a well suited candidate to be confirmed through the DT technique by detecting the doppler shadow during transit. Besides the confirmation of this interesting system we would be able to compute its spin-orbit angle which will make of TIC290403522 one of the longest period transiting planets having an obliquity measurement.

We propose to observe the two partial transits of TIC290403522 that will occur on 2020A (see panels A and B of Figure 1) with FEROS in order to confirm the planetary nature of this system and to determine its obliquity through the DT technique.

We stress that our proposal involves time critical observations. Due to an unsolved problem in the CNTAC web platform, we were not able to assign the exact dates to our two 1n runs. Therefore, here we specify those dates. The first transit opportunity will happen the night of July 31 of 2020. The second transit opportunity will occur the night of August 22 of 2020. We propose to use the FEROS spectrograph on those two specific nights.

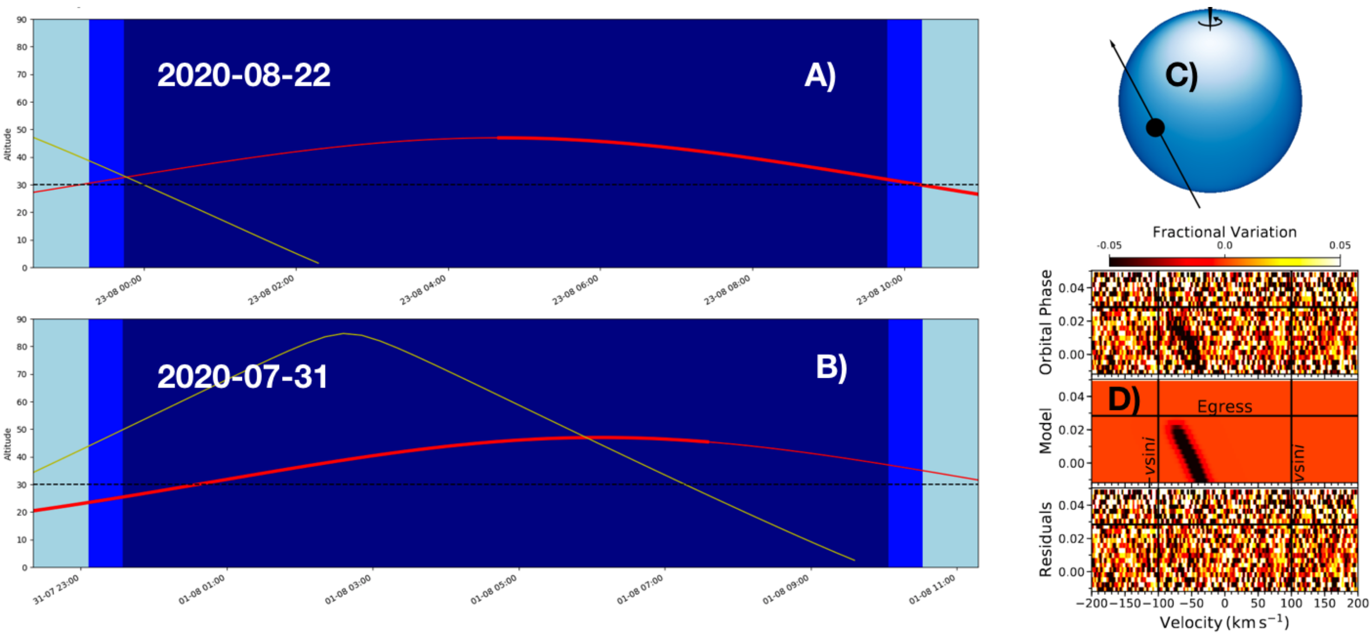

Figure 1): Panel A: Visibility plot for TIC290403522 (red line) for the transit that will occur on August 2020, where the thick line represent the time where the transit is expected to happen. Panel B: same as Panel A, but for the transit of July 2020. Panel C: representation of the spin-orbit angle for the Hot Jupiter HAT-P-70b as obtained from a DT analysis. Panel D: DT measurement for the Hot Jupiter HAT-P-70b obtained with the TRES spectrograph.

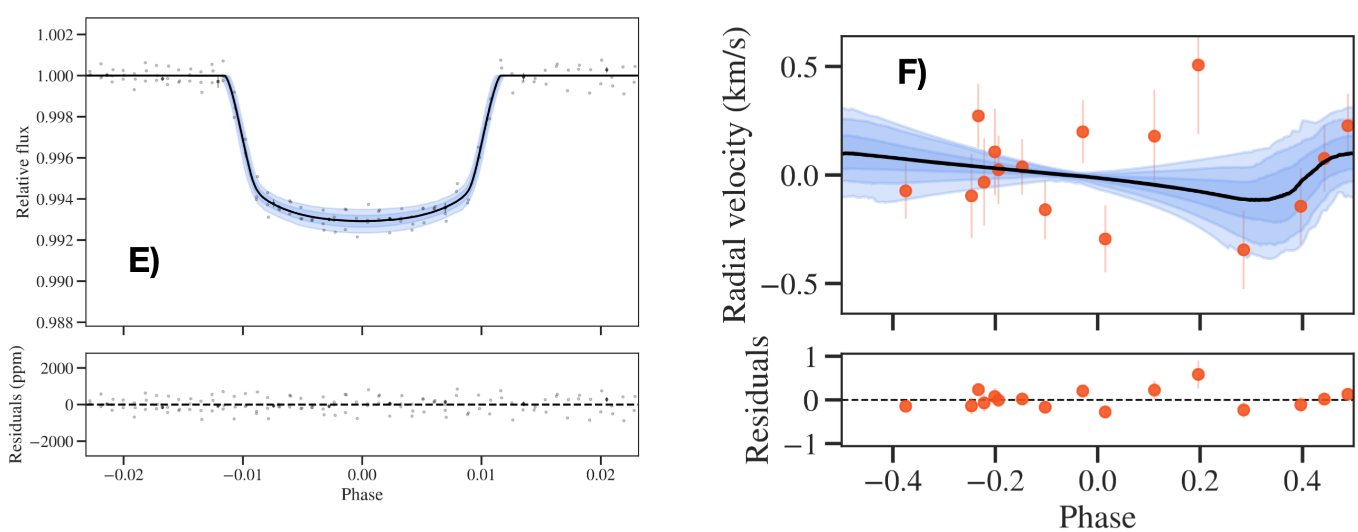

Figure 2): $left$: Phase folded TESS light curve of TIC290403522 showing the ≈6000 ppm transit. $right$: Phase-folded FEROS RVs for TIC290403522 showing a relatively large scatter due to the high rotational velocity of the star. We can put an upper limit of K<400 m/s, which rejects most false positive scenarios involving eclipsing binaries.

CURRENT STATUS OF THE PROJECT

The proposed experiment is framed in the context of a large-scale TESS follow-up program that is described in another CNTAC proposal. That project relies in the RV follow-up and orbital characterization of warm Jupiter candidates from the TESS mission. On the other hand, this proposal consists on performing a DT analysis on a specific target that was identified from our own processing pipeline of the TESS Full Frame Images, developed by the PUC master student Felipe Rojas (co-I of this project). Additionally, PUC master student Pascal Torres (co-I of this project) is working for his thesis in the characterization of planets orbiting rapid-rotating stars. We expect that the results obtained from the proposed experiment will be an important part of his thesis.

Below we list some of the very rencent (year 2019) publications that can be associated to our TESS follow-up project.

- **Jordán, A.**, **Brahm, R.**, Espinoza, N., et al. (**incl. FR, PT**), 2019, *TOI 677b: A Warm Jupiter (P=11.2d) on an eccentric orbit around a late F-type star* AJ submitted.
- **Brahm, R.**, Espinoza, N., **Jordán, A.**, et al. (**incl. FR, PT**), 2019, AJ 158, 45.
- Rodriguez, J.; Quinn, S.; Huang, Ch., et al. (**incl. RB, AJ**), 2019, AJ 157, 91
- Jones, M., **Brahm, R.**, Espinoza, M., et al (**incl. AJ**), 2019, A&A, 565, 16
- Huber, D., Chaplin, W., Chontos, A., et al (**incl. RB, AJ**), 2019 AJ, 157, 245
- Espinoza, N., **Brahm, R.**, Henning, Th., et al. (**incl. AJ**), 2019, MNRAS submitted, arXiv:1903.07694
- Kossakowski, D., Espinoza, N., Brahm, R. et al. (**incl. AJ**), 2019 , MNRAS accepted: arXiv:1906.09866
- Wang, S., Jones, M., Shporer, A., et al. (**incl RB**) 2019, AJ, 157, 51

TECHNICAL DESCRIPTION

We propose to obtain a sequence of spectroscopic observations during the two partial transits that the TESS candidate TIC290403522 will present in 2020A. The idea is to study the variations of the spectral line profile of the star produced by the shadow of the planet blocking regions of the star with different rotational velocity component. We also require several out of transit observations in order to derive the uncontaminated rotational kernel through the de-convolution process. The required SNR per spectra is of at least ≈50 per resolution element (see. Zhou+2016, MNRAS, 460, 3376). While this SNR value is relatively low, the final rotational profile is derived with a much greater SNR because it is built from the combination of most of the spectral lines present in the spectrum. Regions having a significant number of telluric lines are left out of the analysis. Due to its relatively high resolution (R=48000), coupled to its great efficiency and stability, the FEROS spectrograph installed at the MPG 2.2m telescope is the optimal facility offered by the CNTAC to perform the proposed experiment.

DT analysis of transiting planets orbiting rapid rotating stars have been successfully performed for systems of the northern sky with the TRES spectrograph mounted on the 1.5m telescope installed at the Fred Lawrence Whipple Observatory, Mount Hopkins, Arizona, USA (Zhou+2016, MNRAS, 460, 3376, Zhou+2016, AJ, 152, 136, Zhou+2017, AJ, 153, 211). This instrument has a similar resolution than FEROS (R=44000), a similar telescope size, and has allowed the determination of obliquity angles for stars with similar magnitudes and rotational velocities than TIC290403522 (e.g. HAT-P-70, Zhou+2019, AJ, 158, 141, see panels C and D of Figure 1). These examples support the hypothesis that FEROS should be capable of performing the proposed measurement. Additionally most of the DT measurements with TRES have been executed on partial transits which also proofs that we should be able to measure the obliquity for TIC290403522 using partial transits.

We will adopt an exposure time of 500s, which according to our 18 already acquired FEROS observations of TIC290403522 should produce spectra with SNR≈100. This will allow us to obtain 32 and 45 spectra during transit for the transits of July and August, respectively. This assumes an instrument overhead of 60s which mainly comes from the readout process, because the pointing of the telescope doesn't change in between exposures. We will use the simultaneous calibration technique in order to trace any significant environmental changes in the instrument enclosure. Spectra will be processed with the CERES pipeline (Brahm+2017, PASP, 129, 034002) from which we will perform the DT analysis following the method presented in Zhou+2019, AJ, 157, 31 (incl. Brahm). We will compute the rotational kernel of the star by de-convolving the observed spectra using a synthetic template having similar atmospheric properties. The shadow of the planet will be modelled as a Gaussian intrusion to the rotational kernel at each time step. The Gaussian will have width of $\mathrm{R}_P/\mathrm{R}_\star \times vsini$, area of $1-f(t)$ (where $f(t)$ is the flux, blocked by the planet,that makes up the transit light curve), centred about $v_p(t)$ (where $v_p(t)$ is the projected rotational velocity for the region of the star occulted by the planet).

The DT experiment will be also photometrically monitored with the 0.7m robotic CHAT telescope (owned and operated by the researchers of this proposal) in order to precisely know the ingress/egress times and also to detect additional signals that could produce systematic deviations in the DT measurement (e.g. spot crossing events).