INAF – TIME ALLOCATION COMMITTEE

Application for observing time **Category: C**

Period AOT39 (April 2019 – September 2019) **Submit using: www.tng.iac.es/submit.html**

1. Title

Towards a better understanding of the formation of warm and hot Jupiters

2. Abstract

Exoplanetary science has been full of surprises, one is the discovery that planets can orbit their stars on highly misaligned (oblique) or even retrograde orbits. We have already shown that the obliquity of massive, close in planets (hot Jupiters) is shaped and reduced by tidal interactions. However, the origin of the large obliquities is not yet well understood. Obliquities can either be a signpost of planet migration, or are a result of misaligned protoplanetary disks connected to a potentially fundamental process during star formation. We can test the different theories by measuring obliquities for planets in wide orbits (warm Jupiters) as the different theories predict either alignment or misalignment. But transiting warm Jupiters are poorly studied objects. Here we propose to target a key multiplanetary system containing a warm Jupiter, EPIC 249624646. Its large transit duration means we cannot get the entire transit in a single night, but we propose to carry out these observations with the combination of the SUBARU and TNG telescopes, giving us adequate precision to help answering the science case. This is the first ever attempt to conduct sequential observations between Subaru/HDS and TNG/HARPS-N.

3a. Number of requested hours per telescope and instrument

TNG					REM	
DOLORES	**DOLOR.+MOS**	**NICS**	**HARPS-N**	**GIANO-B**	**ROSS**	**REMIR**
			6	6		

3b. Observing modes

TNG:	X	**Visitor**		**Service**		**ToO**
REM:		**Rapid Response**		**Queuing**		**ToO**

4a. Preferred months

first choice: April second choice:

4b. Other scheduling constraints (use also box 14)

These are time critical observations as we target a planetary transit.

5a. Past and future of the project

a) Hours already awarded to the project: 12

b) Hours foreseen to complete the project: 0
(not including this request)

6. Principal investigator (Nordic Time)

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7. Co-investigators (name and institution)

Teruyuki Hirano, Tokyo Institute of Technology
Simon Albrecht, Aarhus University (Stellar Astrophysics Centre)
Bun'ei Sato, Tokyo Institute of Technology

8. Status of the project

Telescope	Instrument	Date	Hours	Notes
TNG	HARPS-N	2017-10-31	4	A similar warm Jupiter system (HAT-P-54) was observed at TNG, and the paper is right now in preparation. The proposed observation is for another system. It is completely independent of the observations of HAT-P-54, but will be a part of the same PhD thesis.
TNG	HARPS-N GIANO-B	2018-11-16	8	A similar warm Jupiter system (HD 286123) was awarded observing time at the TNG, but the observations did not succeed due to bad weather.

Description

The observations of HAT-P-54 (and HD 286123) are completely independent observations from the one of EPIC 249624646 proposed here, but will form a part of the same PhD thesis. The paper on HAT-P-54 is in preparation and we will try to get new observing time for HD 286123 when the transit-timing is right.

Publications

9a. If this proposal is a part of a PhD thesis, write here the name of the student, the thesis title and briefly describe the relevance of these observations for the thesis goals.

M. Hjorth, *The origin of hot Jupiters*, The observations will probe the origin of hot Jupiters by studying the architecture of warm Jupiters with large star-planet separations. This observation form a core part of the PhD project.

9b. Is this, or a similar application submitted to other time allocation committees (e.g. ESO, TNG-CAT, ITP)? If yes, please specify which and explain if and why the proposals should be considered complementary.

For the upcoming semester, the first half of the transit of EPIC 249624646 is observable from SUBARU and the second half from the TNG. We have submitted an application to SUBARU for the first part of the transit (pending).

10. Description of the programme (max. 3 pages, including references, tables, and figures.)

A) Scientific rationale One of the biggest surprises in exoplanetary science emerged at the dawn of the field: the existence of giant planets having orbital distances much smaller than an astronomical unit (AU): hot Jupiters. As gas giant planets can only form at distances of several AU from their host stars, a so far unidentified mechanism causes this dramatic shrinking of the orbital semi-major axes. The two leading types of theories able to account for these short orbital distances, disk in-spiral (e.g. Lin et al. 1996), and dynamical interactions (e.g. Fabrycky & Tremaine 2007; Nagasawa et al. 2008) make different predictions about the stellar obliquities with respect to the planetary orbital plane. Therefore, measuring stellar obliquities holds the key to understand the formation of these alien worlds better. If the system exhibits transits, it is possible to detect anomalies in the spectral absorption lines of the eclipsed star, which have their origin in the partial blockage of the rotating photosphere; the Rossiter-McLaughlin (RM) effect. Its manifestation depends on the angle between the projections of the stellar rotation axis and orbital axis of the occulting companion.

Obliquity measurements have been conducted for more than 140 exoplanetary systems, almost all of them hot Jupiters. They have revealed a diversity of orbits, including well-aligned systems (see, e.g., Queloz et al. 2000), misaligned systems (Hébrard et al. 2008) and even retrograde systems with opposite senses of rotation and revolution (Winn et al. 2009, Triaud et al. 2010). For a time the picture was confusing, but then a pattern was discovered: planets in systems with low obliquity orbits cool low-mass stars, while planets in high-obliquity systems orbits hot massive stars (Winn et al. 2010). The low-obliquity systems seems to be the ones for which tidal coupling between the planet and star is strongest, because the stars have convective envelopes and the orbital separations are small (Albrecht et al. 2012a). This suggests that the orientations of the orbital planes of hot Jupiters were nearly random when they arrived in the vicinity of their host stars, and that the low obliquities that are often observed are a consequence of star-planet tidal interactions. This implies, in turn, that the origin of hot Jupiters involves dynamical interactions (such as planet-planet scattering or the Kozai effect) that tilt their orbits, rather than inspiraling due to interaction with a protoplanetary disk (Albrecht et al. 2012a). Thus, spin-orbit measurements have enabled decisive progress on the most enduring problem in exoplanetary science: the origin of hot Jupiters.

However, this conclusion hinges on an important assumption: The protoplanetary disk was aligned with the stellar equator. Theorists have cited the possibility that stars and their disks are frequently misaligned at an early stage for reasons unrelated to planets. Proposed mechanisms include chaotic star formation (Bate et al. 2010) and torques due to neighboring stars (Batygin 2012), but these fail to explain the distinction between observed obliquities of cool and hot stars (Dai & Winn 2017). Recently, a disk-torquing mechanism tilting the disk and **simultaneously** depending on stellar temperature was presented (Spalding & Batygin 2015). Here the inner edge of the protoplanetary disk of hot massive stars is tilted due to magnetic interactions, followed by disk in-spiral of the resulting misaligned planets.

Fortunately, there is a way to clarify whether large obliquties originate from tilted protoplanetary disks or multi body interactions: measuring obliquities of stars with convective envelopes and planets on large orbital separation (warm Jupiters). If large obliquities originate from dynamical interactions, then such systems should have large obliquities. This is because the timescale for tidal realignment scales with $(a/R_\star)^6$ and therefore tidal realignment is unimportant in these systems. In contrast, if large obliquities originate from the disk-torquing mechanism acting in systems with hot stars (Spalding & Batygin 2015), then we expect low obliquities. These planets are also interesting in their own right, as transiting warm Jupiters are poorly studied objects.

B) Scientific aim Unfortunately known systems with cool stars and gas giants on larger separations amendable to obliquity measurements are rare. However EPIC 249624646 is just such a system (Hjorth et al. in review). We have analysed this system using *Kepler* photometry in combination with aquired RVs from HARPS@ESO, HARPS-N@TNG, FIES@NOT and AO imaging from IRCS@SUBARU, and are confident in the planetary validation and system parameters (Fig. 2). It consists of an inner mini-Neptune and warm Jupiter on a large scaled semi-major axis ($a/R_\star = 40.1 \pm 1.5$), both transiting a slightly evolved F8 star, which is bound to two wide-orbit M dwarfs. The multiplanetary nature of this system, means that we also might be able to test whether warm Jupiters follow two formation channels, as it is speculated that the presence of inner siblings to warm Jupiters is a sign of *in situ* formation (Hamers et al. 2017).
Given EPIC 249624646's brightness (V=11.11), the exposure time, transit duration and system parameters we expect a radial velocity (RV) precision with combined measurements from HDS and HARPS-N sufficiently high to obtain an accuracy of ~ 5 deg in the projected obliquity (see box 12 and Fig. 3, 4), adequate to help answer the science question discussed above. It is essential to combine the HDS and HARPS-N measurements, since the long transit duration makes it impossible to observe the entire transit in a single night. The observation of EPIC 249624646 is important as the number of jovian planets with large scaled semi-major axes still remains at half a dozen, not allowing for a statistically meaningful sample. With the proposed obliquity measurement and by observing exoplanet systems with similar characteristics, we aim at rectifying this situation. If possible, we would also like to use GIANO-B simultaneously (GIARPS). Doing this we can probe the atmosphere by measuring the slope of the Rayleigh scattering from the chromatic RM effect (as done in Gloria, Snellen and Albrecht 2015). Furthermore, activity-induced RV variations is mitigated in the near-infrared, which enables a more robust detection of the RM signal. However, GIANO-B is not critical for the success of the science case.

In summary: We propose here to observe the EPIC 249624646 exoplanet system with HARPS-N (and GIANO-B) to measure the stellar obliquity in this system. This obliquity measurement of a multiplanet system with a large scaled star-planet separation is rare but important in the context of theories trying to explain the formation and evolution of hot Jupiter systems, a long standing riddle in exoplanet science. It would be the first ever attempt to conduct sequential observations between Subaru/HDS and TNG/HARPS-N.

Data Reduction and Publication Plan: For the proposed observations we will both employ traditional RV anomaly measurements using our improved model (Hirano et al. 2011c and Fig. 3), and also measure line deformations in stellar absorption lines directly (Fig. 1). The latter model was originally developed for double lined binaries (e.g. Albrecht et al, 2007, 2009, 2014), but also enabled a secure ($\lambda = -0.5 \pm 5.7$ deg) planetary RM measurement even with a shallow transit (1339 59ppm; Albrecht et al. 2013). If stellar flares would occur during our observations then our code is able to identify them as deformations of the line shapes, avoiding systematic biases in the RM measurement. We expect a fast data analysis and submission of a publication shortly after observations. The PhD student who already carried out the confirmation and characterization as well as the simulations seen in Fig. 3 will lead this project with supervision by the CoIs. By also doing simultaneous GIANO-B (GIARPS) observations we will be able to measure the chromatic RM effect and study the planet's atmosphere, as we did in Gloria, Snellen and Albrecht 2015. However, GIANO-B is not a requirement for the success of the science case.

References: Albrecht et al. 2014, ApJ, 785, 85; Albrecht et al. 2013, ApJ, 771, 14; Albrecht et al. 2012a, ApJ, 757, 18; Albrecht et al. 2012b, ApJ, 744, 189; Albrecht et al. 2011, ApJ, 738, 50; Albrecht et al. 2009, Nature, 461, 373; Albrecht et al. 2007, A&A, 474, 565; Bate et al. 2010, MNRAS, 401, 1505; Batygin, 2012, Nature, 491, 418; Brogi et al. 2012, Nature, 486, 502; Dai & Winn, 2017, sub. AAS journals arXiv:1702.04734; Fabrycky & Tremaine 2007, ApJ, 669, 1298; Gloria, Snellen & Albrecht 2015, A&A, 580, 84; Hamers et al. 2017, MNRAS, 466, 4107; Hébrard et al. 2008, A&A, 488, 763; Hirano et al. 2011a, PASJ, 63, 57; Hirano et al. 2011b, PASJ, 63, 531; Hirano et al. 2011c, ApJ, 742, 69; Hirano et al. 2012, ApJL, 759, 36; Hirano et al. 2016, ApJ, 825, 53; Lin et al. 1996, Nature, 380, 606; Nagasawa et al. 2008, ApJ, 678, 498; Queloz et al. 2000, A&A, 359, 13; Sato et al. 2002, PASJ, 54, 873; Spalding & Batygin 2015, ApJ, 811, 82; Snellen et al. 2010, Nature, 465, 1049; Triaud et al. 2010, A&A, 524, 25; Van Eylen et al. 2014, ApJ, 782,14; Winn et al. 2009, ApJL, 703, 99; Winn et al. 2010, ApJL, 718, 145;

Figures

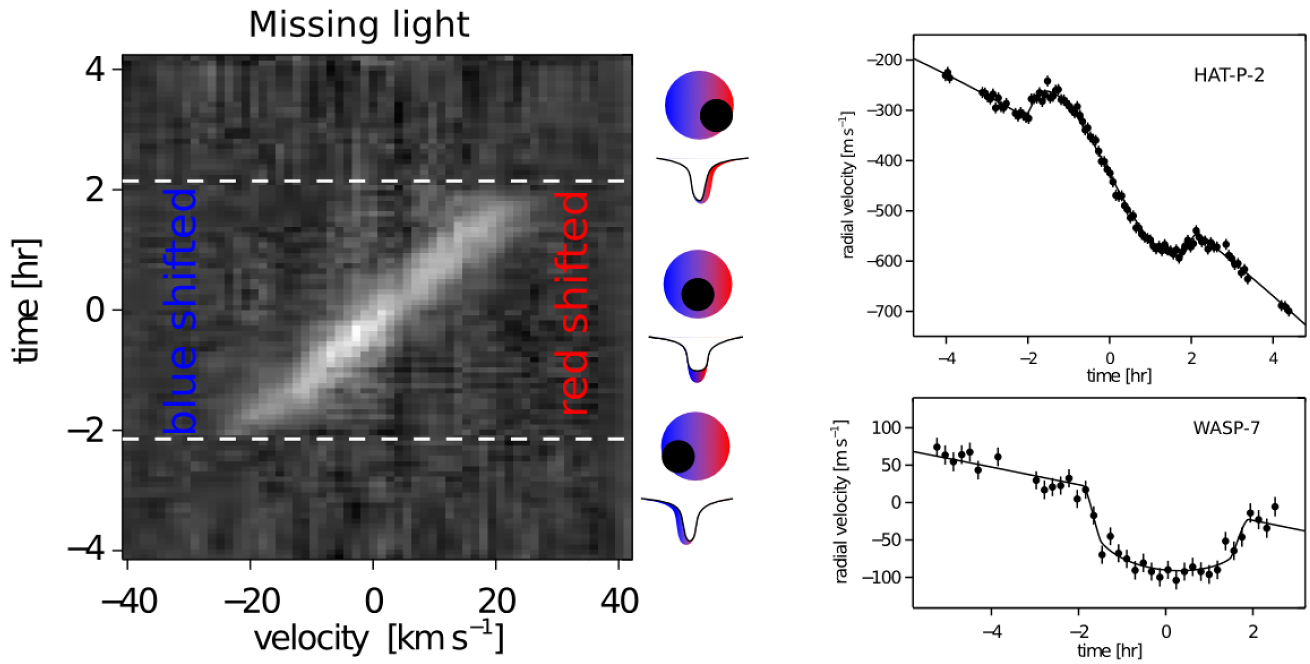
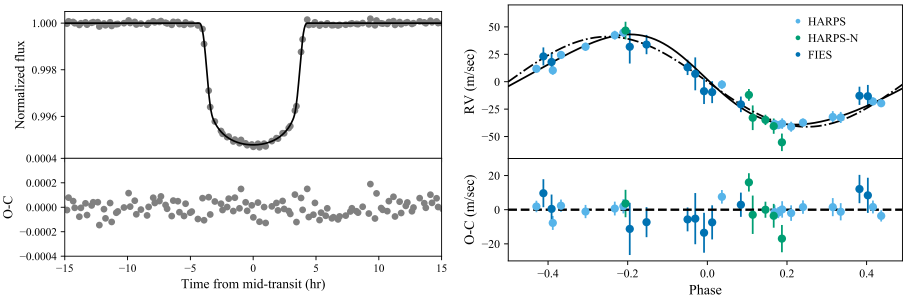


Figure 1: The Rossiter-McLaughlin (RM) effect. During the transit of a planet in front of its star different parts of the stellar absorption lines are hidden from view. *Left panel:* The missing component of the stellar absorption lines (bright colors) during a transit of a hot-Jupiter in the HAT-P-2 (m_V=8.69) system. At the beginning of the transit, parts of the approaching stellar surface area are hidden from view and blueshifted light is missing. At the end, redshifted light is missing. *Top right panel:* RVs measured during this transit. One can see the change in radial velocity due to the orbital radial velocity and the RM effect. *Lower right panel:* The RM effect in the WASP-7 system reveals that the stellar rotation is tilted by $86 \pm 6°$ against the orbital angular momentum (Albrecht et al. 2012b).



Parameters	Value
P (days)	48.36692(41)
$a/R_\star$	40.1(15)
$K_\star$ (m s^{-1})	41.1(17)
e	0.144(33)
M_p/M_J	0.819(48)
R_p/R_J	0.993(50)

Figure 2: The discovery and validation of EPIC 249624646. Using *Kepler* photometry in combination with aquired RVs from HARPS@ESO, HARPS-N@TNG, FIES@NOT and AO imaging from IRCS@SUBARU we have confirmed and characterised the planetary system of EPIC 249624646 (Hjorth et al. in review), revealing a mini-Neptune and warm Jupiter in a triple star system. *Left:* the photometric lightcurve of the warm Jupiter. *Middle:* the radial velocity curve of the warm Jupiter together with it's best-fit orbit (solid) and a circular orbit (dashed). *Right:* selected system parameters of the warm Jupiter.

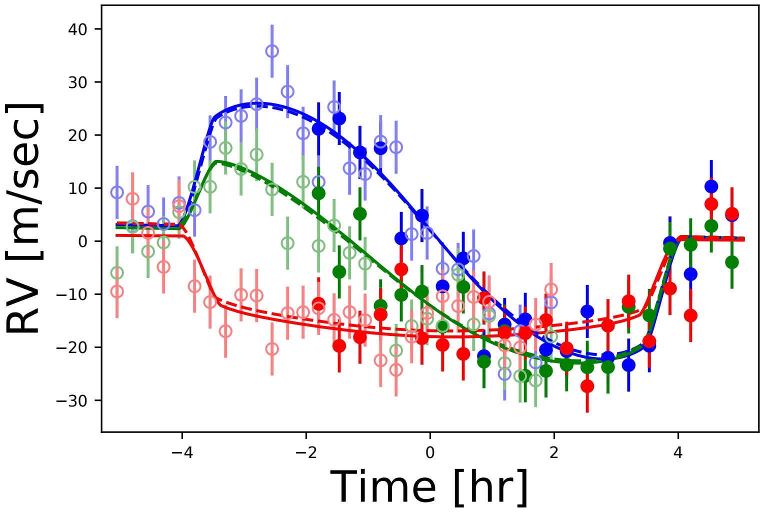


Figure 3: The predicted Rossiter-McLaughlin effect in the EPIC 249624646 system from the combined HDS@SUBARU and HARPS-N@TNG observation. Using the system parameters derived from our analysis and an RV scatter of 5 m s^{-1} for HARPS-N we simulated measurements of the projected obliquity in this system. The solid data points represents the simulated HARPS-N observations, while the shaded data points depicts the simulated HDS data. The blue, green and red solid lines show three different assumed obliquities (0 deg, 45 deg and 90 deg). The best solutions from our MCMC runs on the simulated RV data leads to the dashed lines.

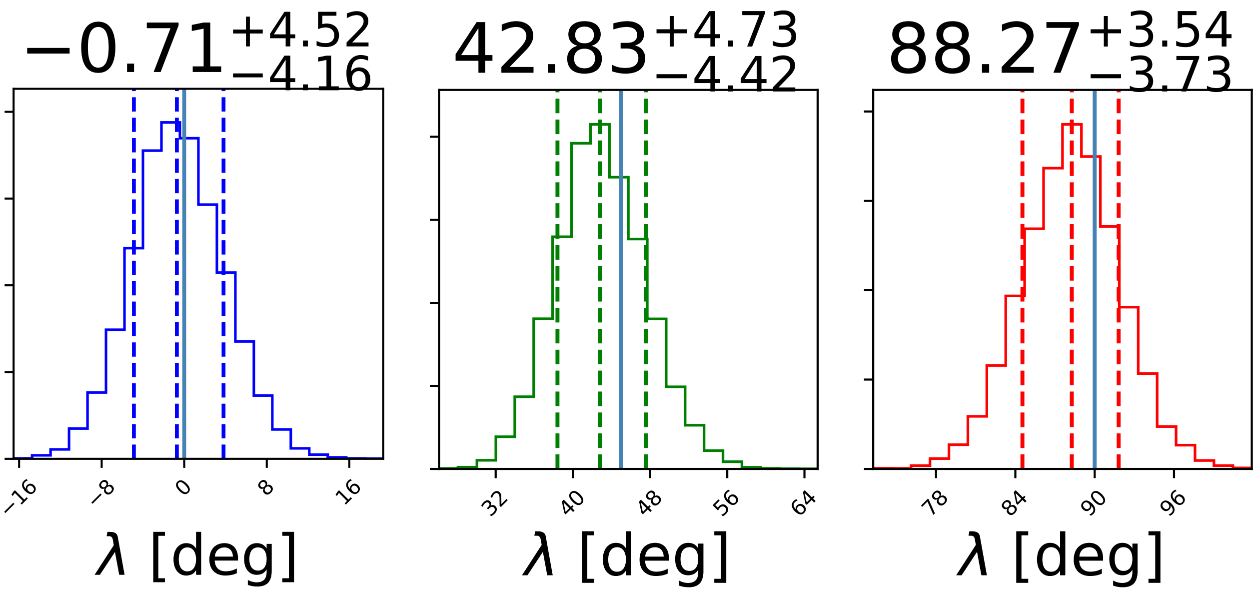


Figure 4: The precision in the obliquity for the EPIC 249624646 system from the combined HARPS-N@TNG and HDS@SUBARU observation. The posteriors of our MCMC results for the three simulated data sets, which assume projected obliquities (λ) of 0°, 45° and 90°, respectively, together with the internal MCMC errors.

11. List of targets (note that the absence of a proper object list and information may weaken the proposal)

Name	α	δ	Epoch	Mag.	Time	Additional Information
EPIC 249624646	15 39 25.865	-20 11 55.74	J2000	V11.11	21600	Standard configuration. These are time critical observations as we target a planetary transit. The only suitable night this semester is April 25/26 2019. The observing run should last 6 hr and should take place at April 25/26 23.40-05.40 UT.

12. Observational strategy and justification of requested time, including overheads.

Measuring projected obliquities via the RM effect requires high cadence and high signal-to-noise observations. The transits of the warm Jupiter in the EPIC 249624646 system last approximately 8 hr and at least 1 hour before and after transit are needed for the RV calibrations. Because of the long orbital period and large transit duration, there is only a few opportunities to observe its transit from Earth-based observatories. **It is almost impossible to observe a full transit from a single observing site and combining the observation from multiple observing sites is essential**. For the upcoming semester, the first half of the transit is observable from SUBARU and the second half from the TNG. In addition, we aim to characterise its atmosphere by measuring the chromatic RM effect, taking advantage of the combined HARPS-N and GIANO-B mode (although not critical for the science case). We therefore request a **single night of at least 6 hr observation using TNG**. Using the ETC for HARPS-N ($V = 11.11$) with a 20-min integration, we expect an internal RV uncertainty of $\sim 5\,\mathrm{m\,s^{-1}}$ (which we have also reached using HARPS-N outside of transit) and SNR of ~ 25 for an F star with $v \sin i \sim 6.5$ km s^{-1}. For GIANO-B we expect an SNR of 35-40 with an exposure time of 600 sec for a single spectrum. Using this RV scatter, we have run several Monte Carlo simulations to estimate the accuracy in the projected obliquity (λ) measurements. The star is fairly quiet, and we do not expect a significant noise contribution to the RV from it. We find that we will be able to determine λ to a precision of $\sim$ 5 deg (Fig. 3, 4).

This observation is time critical as we target a planetary transit. Two nights are available this observing period: the second part of the transit from HARPS-N@TNG on April 25 2019 and the first part of the transit on June 13 at HDS@SUBARU, which satisfy the constraints of getting 1 hour post-egress and pre-ingress observations, respectively. The observing run at TNG should last 6 hr and should take place at April 25/26 23.40-05.40 UT.

13. Requested instrument(s) setup

Id	Instrument	Binning	Filter(s)	Slit	Grism	Time	Additional Information
1	HARPS-N	1x1	V	none	none	6hr	Time critical observations (planetary transit). Suitable night: April 25/26. The observing run should last 6 hr and should take place at April 25/26 23.40-05.40 UT.
2	GIANO-B	1x1	YJ	none	none	6hr	Combined HARPS-N and GIANO-B (GIARPS). Observations with GIANO-B is optional for the science case, but will characterise the planetary atmosphere.

14a. Moonlight constraints

Max. # of days from new moon ☐

14b. Scheduling constraints, special requirements and other remarks
(please include justification of constraints in 14a)

These are time critical observations (planetary transit). Suitable night: April 25/26. The observing run should last 6 hr and should take place at April 25/26 23.40-05.40 UT.

15. Observational background of the applicants

Name of the observer(s) at TNG: Maria Hjorth, Simon Albrecht

Experience of the observer(s) with the requested TNG instrument(s)
Albrecht have ample experience with HARPS-N. Hjorth has ample experience with HARPS-N and GIANO-B in GIARPS mode.

Experience of the observer(s) with other telescopes/instruments
We have ample experience observing and analyzing high-resolution echelle spectra taken during transits and eclipses. We have experiences with the HARPS, HARPS-N, HIRES, FIES, PFS, Hamilton, HDS, and Sophie spectrographs. We achieved the first identification of a close double star system in which both stars are spinning on their sides relative to the orbit (Albrecht et al. 2009). We have published as first authors RM measurements on more than 20 exoplanet systems (Albrecht et al. 2011, 2012a, 2012b, 2013), and have improved on the modelling of the radial velocity anomaly caused by the Rossiter-McLaughlin effect (Hirano et al. 2011c). We also contributed to the analysis of high resolution near IR spectra (CRIRES), having been the first to detect the motion of a planet directly (Snellen et al. 2010), and the first to measure the orbital motion of a non transiting planet directly (Brogi et al. 2012).