European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME — PERIOD: 100A

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted.

1. Title — Category: C–7

Probing the emission spectrum of WASP-121b: the first use of i- & z-band spectro-photometry

2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 12 hours SM

Spectro-photometry has been used with great success to obtain the transmission spectra of hot Jupiters, with current programs using WFC3 and FORS2. However, secondary eclipse observations of hot Jupiters have to date almost solely used broadband photometry. Spectro-photometry has several advantages, including its ability to unambiguously identify individual molecules in a spectrum. We propose to observe two secondary eclipses in wavelength range 7370 - 10700 Å of WASP-121b, an ultra-short period hot Jupiter with excellent suitability for such a study. This will allow us to identify the TiO and VO features in this window and test a recent report of their detection in the WASP-121b transmission spectrum. This will not only demonstrate the ability of FORS2 to obtain high-quality secondary eclipse data using spectro-photometry, but will be the first time any telescope has used this method to observe exoplanetary secondary eclipses at these wavelengths.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	100	FORS2	12h	jan	g	n	THN	s	

4. Number of nights/hours — Telescope(s) — Amount of time

a) already awarded to this project:

b) still required to complete this project:

5. Special remarks:

We are requesting two sets of 6 hours on nights that coincide with visible secondary eclipses of WASP-121b, therefore a total of 12 hours across 2 nights. See section 12 for a full list of nights during which an eclipse is visible.

6. Principal Investigator:

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6a. Co-investigators:

C.A.	Watson	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK
N.P.	Gibson	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK
E.	de Mooij	Other,IE
A.	Thompson	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK

Following CoIs moved to the end of the document ...

7. Description of the proposed programme

A – Scientific Rationale: Since the initial detections of planetary thermal emission, there have been widely varying interpretations of whether we observe temperature inversions in the atmospheres of hot Jupiters, and what gives rise to them in these extreme conditions. Hubeny et al. (2003) predicted that the strongly absorbing compounds TiO and VO could be present in appreciable quantities in the upper atmospheres of hot Jupiters, which would be likely to give rise to temperature inversions. Since this prediction, there have been continuous attempts to both observe these compounds in planetary transmission and emission spectra, and specify the exact conditions under which they will be present in the upper atmosphere. Fortney et al. (2008) proposed that TiO and VO and consequently inversions, would only be present in the atmospheres of the most highly irradiated hot Jupiters. Knutson et al. (2010) proposed that inversions are not present in hot Jupiters orbiting highly active stars as the TiO and VO compounds in the upper atmosphere are destroyed due to the higher levels of stellar activity, with the opposite true of less active stars. Madhusudhan (2012) proposed that planets with a C/O ratio > 1 have most of their oxygen bound up in CO molecules, hence suppressing the amount of atmospheric TiO and VO, and therefore the planet's ability to host an inversion, with the opposite true for C/O < 1. However, specific observations subsequent to these prediction appear to contradict each of them. As more data have become available and atmospheric models have developed further, most reported instances of temperature inversions have been challenged. The ability to observe the thermal emission from newly discovered ultra-short period hot Jupiters will act to test the validity of the above theories further.

To date the vast majority of ground-based secondary eclipse measurements have been conducted using broad-band photometric observations. Whilst this indisputably gives useful information that allows constraints to be put on the atmospheric composition and temperature-pressure profile, there are some notable drawbacks. In any broad wavelength band there will be many different molecular features that could act to increase or suppress the detected eclipse depth. Measurement over a wide band only allows constraints to be put on the combination of such compounds in the atmosphere, and does not allow the unambiguous detection of individual features. Photometry of secondary eclipses is also an inefficient way of taking data, given that for most instruments any given eclipse can only be observed with one filter at a time. The technique of differential spectro-photometry addresses both of these problems. Each of the time-series spectra is divided into distinct wavelength channels, allowing features associated with specific molecules to be identified. The technique also allows common mode corrections to the lightcurves for each wavelength bin (see Gibson et al. 2013), allowing the systematics known to dominate such observations to be minimised. Spectro-photometry is routinely used for transmission spectroscopy of hot Jupiters, with major programs approved for instruments including WFC3 (e.g. Kriedberg et al., 2014a) and FORS2 (Nikolov et al., 2016, Gibson et al., 2017, see Fig. 1) producing a wealth of high-quality data in recent years. Spectro-photometry has been used sparingly in the studies of secondary eclipses, and only in the J-band and redward, with the most notable examples using WFC3. Recent publications include the detection of water features in the emission spectra of WASP-43b (Kriedberg et al., 2014b) and HD 209458b (Line et al., 2016), and the tentative inference of a temperature inversion for WASP-33b (Haynes et al., 2015). However, such studies have rarely been attempted with ground-based facilities, and to the best of our knowledge have never been attempted using FORS2, despite its well-publicised successes in transmission spectroscopy.

WASP-121b is a newly discovered hot Jupiter whose ultra-short orbital period (P = 1.27 d) puts it very close to being tidally disrupted. The combination of its small orbital separation, its hot F6V-type host star and its highly inflated size gives it almost unparalleled suitability for atmospheric categorisation using observations of its transmission and emission spectra. Indeed, it has been the subject of much recent attention due to evidence of TiO and VO being observed in its transmission spectrum (Evans et al. 2016). Delrez et al. (2016) measured a photometric z'-band eclipse depth of 603 ppm (see Fig. 1), to date one of the few cases where the thermal emission is detectable in this window (e.g. Smith et al. 2011, Burton, Watson, Gibson et al. 2012, Föhring et al. 2013).

B – Immediate Objective: We propose to use differential spectro-photometry with FORS2 to observe two secondary eclipses of WASP-121b. We will use the 600z grism, which will give us coverage over the i- and z-bands in the range 7370 - 10700 Å. *This will demonstrate the ability of FORS2 to obtain high-quality spectro-photometric secondary eclipse data, as well as being the first spectro-photometric exoplanetary secondary eclipse measurement at these wavelengths.*

As observations at these wavelengths probe the planetary emission in the Wien limit, they are very sensitive to the precise temperature of the emitting layers. Whilst this is shortward of the peak of the planet's thermal emission distribution, it is an important window where the C/O ratio of highly irradiated planets such as WASP-121b can be tested. Indeed, the z'-band secondary eclipse measurement of WASP-19b conducted by members of this group (Burton, Watson, Gibson et al, 2012) was cited as an "important discrimination" point for determining its C/O ratio (Madhusudhan et al. 2012). This is because highly irradiated planets that have a low C/O ratio should display noticeable TiO and VO absorption between 7000 – 11000 Å. If the planet has a high C/O ratio, however, then TiO and VO are depleted and thus there are no absorption signatures visible. When coupled with observations at longer wavelengths, this can also be used to constrain the temperature-pressure

Description of the proposed programme (continued)

profile of the upper atmosphere. WASP-121b is an extremely rare example of a highly irradiated planet orbiting a bright host star where the relatively modest thermal emission at such short wavelengths is measurable with current technology. *The use of spectro-photometry at these wavelengths will enable the identification of TiO and VO features in the dayside of WASP-121b, which will allow us to test the reported detection in the planet's terminator by Evans et al. (2016).*

These proposed observations will provide strong constraints on the planet's SED and are therefore also valuable in the absence of TiO. Since our team have already conducted z'-band eclipse measurements for WASP-19b and WASP-103b (which we are currently analysing), we will be able to make a direct comparison of the inferred atmospheric properties for these planets. This will enable any common features or differences to be identified for this extreme class of gas-giant, and help constrain the C/O classification scheme for hot Jupiter atmospheres. The use of spectro-photometry will also allow us to identify water absorption features in this window.

Strategy - Differential spectro-photometry involves the use of a multi-object spectrograph to simultaneously obtain spectra of several comparison stars in the field of view. Each spectrum is divided into distinct wavelength channels, and the light curves of the comparison stars are used to correct the light curves of the target star in each wavelength bin. This produces high precision transit light curves as a function of wavelength. The goal is to measure the secondary eclipse depth as a function of wavelength, requiring precision of typically 10^{-4}.
We will use FORS2 in MOS mode to simultaneously observe the WASP-121 and several comparison stars in the field of view. Following pre-imaging, we will design a custom mask with slits of 15 arcsec width for the target and two comparison stars; this will ensure that small variations in the pointing and seeing will not lead to any slit losses. The slits will be 45 arcsec in length to ensure that sufficient sky near the star is sampled. We will use the 600z grism with the OG590 order blocking filter and a central wavelength of 9010 Å, giving a wavelength coverage of ≈ 7370-10700 Å. Differential light curves as a function of wavelength will then be produced and the planet-to-star flux ratio will be measured as a function of wavelength to produce the emission spectrum. We will then compare our data to theoretical models in order to confirm the presence of TiO and VO, and calculate the brightness temperature at the altitudes probed by each of our wavelength bins.

Attachments (Figures)

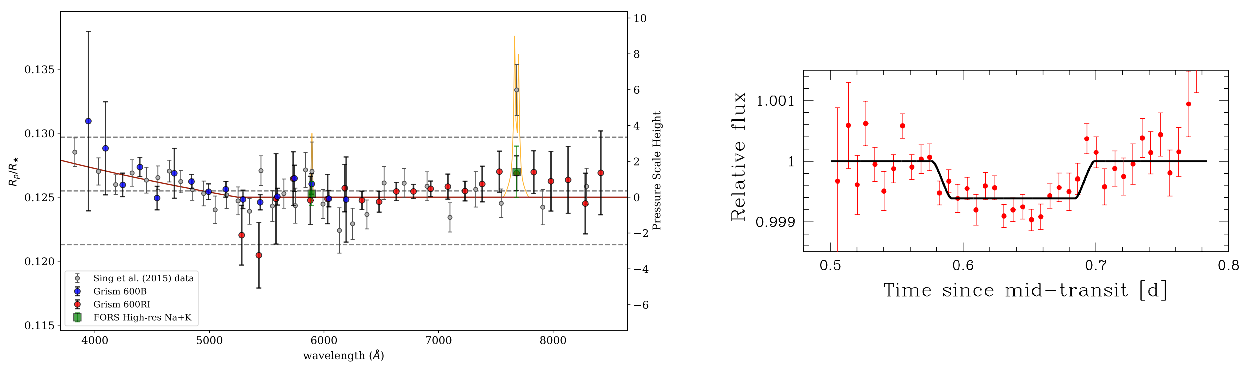

Fig. 1: Left: transmission spectrum of WASP-31b obtained using FORS2 (Gibson et al., 2017), achieving typical precision of $\sim 10^{-4}$ in the transit depth in $\sim$ 10 nm bins. Right: z'-band secondary eclipse photometry of WASP-121b obtained using TRAPPIST-S (Delrez et al., 2016). The detection is significant at the 4-σ level, and the solid line indicates the best fitting model with a depth of 603 ± 130 ppm. Our proposed observations will enable us to measure this at >5-σ per 10 nm bin.

References: Burton, Watson, Gibson et al. 2012, ApJS, 201, 36; Delrez et al. 2016, MNRAS, 458, 4025; Evans et al. 2016, ApJ, 822, L4; Föhring et al. 2013, MNRAS, 435, 2268; Gibson et al. (2013), MNRAS, 436, 2974; Gibson et al. 2017, MNRAS, *accepted*; Haynes et al. 2015, ApJ, 806, 146; Hubeny et al. 2003, ApJ, 594, 1011; Kriedberg et al. 2014a, Nature, 505, 69; Kriedberg et al. 2014b, ApJ, 793, 6; Line et al. 2016, AJ, 152, 203; Madhusudhan, 2012, ApJ, 758, 36; Nikolov et al. 2016, ApJ, 832, 191; Sedaghati et al. 2015, A&A, 576, L11; Smith et al. 2011, MNRAS, 416, 2096.

8. Justification of requested observing time and observing conditions

Lunar Phase Justification: WASP-121b is sufficiently bright that the dominant sources of noise are Poisson noise from the object and scintillation. Furthermore, at these wavelengths the sky brightness does not vary dramatically with lunar phase. However, previous experience shows that sky-background variations can introduce significant correlations within the data, and for this reason we do prefer dark or grey time. All secondary eclipse dates have been checked for moon distances, and there are no dates when the moon-target separation is less than 50°.

Time Justification: (including seeing overhead) We request a total of 12 hours, consisting of 6 hours on two separate nights to coincide with visible WASP-121b secondary eclipses. An eclipse of WASP-121b lasts 173 minutes, and we require at least 3 hours of out-of-eclipse light to accurately calibrate the eclipse depth, which totals $\sim$ 6 hours. Given that our observations are often dominated by instrumental systematics, we request to observe two eclipses to confirm our results.

WASP-121 has a V-magnitude of 10.44, and the comparison stars have V-mags of $\sim$ 10.10 and 11.90. We note that the following figures are calculated for WASP-121 and not the slightly brighter comparison, but the exact exposure time can be adjusted on each night to match the conditions and minimise the overheads, as done for our previous observations. We will use an exposure time of 20 seconds to keep the target well within the saturation limit of the detector. We will observe using the non-standard 'low gain' mode (200kHz,2x2,low), which increases the number of photons we can collect before saturation and significantly reduces the readout time to $\sim$ 26s. From our experience, we require 3 hours of out-of-eclipse light to accurately calibrate the eclipse depth. During a 6 hour observation, we can obtain 469x20s exposures with a cadence of $\sim$ 46s, 225 of which are within the eclipse. We expect to reach of a S/N of $\sim$ 320 at the central wavelength, and $\sim$ 4800 when summing up the eclipse observations.

The S/N levels reached should easily be enough to probe for TiO/VO features in the atmospheres. However, the real bottleneck is instrumental systematics, that our observing strategy has been very successful at minimising in the past. We expect to achieve comparable precision of $\sim 10^{-4}$ if conditions are stable, and should be able to detect the TiO/VO signal. Nonetheless, we request two eclipses to confirm the signal and ease modelling of systematics.

8a. Telescope Justification:

Precise spectro-photometry of exoplanetary secondary eclipses requires large aperture telescopes. It also requires a multi-object spectrograph, which is a function of FORS2. VLT/FORS2 has a proven track record of using spectro-photometry to obtain high quality exoplanetary transmission spectra (for example Nikolov et al. 2016, Gibson et al. 2017). A large transmission spectroscopy program using FORS2 has been accepted and is ongoing (P.I. Nikolov, Co-I Gibson, also Co-I of this proposal), and other groups also use FORS2 for the same purpose (e.g. Sedaghati et al. 2015). We note that to the best of our knowledge, FORS2 has not been used for spectro-photometry of exoplanetary secondary eclipses before. Based on the quality of the published FORS2 transmission spectroscopy data, we expect that the quality of the FORS2 secondary data will rival that of the published HST/WFC3 secondary eclipse spectro-photometry.

8b. Observing Mode Justification (visitor or service):

We prefer our observations in service mode, given that the observations are time-critical and are in 6 hour blocks between November and March, sometimes with long gaps between observations. The team has a lot of experience in these observations, which will involve staring at the same target for 6 hours. We would also happily travel to Chile to perform the observations if it is deemed desirable.

8c. Calibration Request:

Standard Calibration

9. Report on the use of ESO facilities during the last 2 years

099.C-0763: *Peeking above the clouds: exoplanet atmospheres at high spectral resolution with UVES.* Gibson, De Mooij, Watson et al.
099.C-0738: *Long term monitoring during the 2017/2018 Hill sphere transit of the young exoplanet beta Pictoris b.* De Mooij, Hooton, Watson, Gibson, Thompson, et al.
599.C-0751: *Characterising the material around the young exoplanet beta Pictoris b* De Mooij, Hooton, Watson, Gibson, Thompson, et al.
098.C-0547: *Solving the TiO mystery in hot exoplanets: high-resolution transmission spectroscopy of WASP-121b.* Gibson, De Mooij, Watson et al.
Data for the above four have recently been acquired, and analysis is in progress
095.C-0162: *Catching a speeding exoplanet: TiO lines in the atmosphere of the extremely hot Jupiter WASP-18b* De Mooij, Watson et al. Analysis of all 4 epochs with useful data are in progress, however, initial results indicate that there is no TiO present in the atmosphere of WASP-18b.

9a. ESO Archive - Are the data requested by this proposal in the ESO Archive (http://archive.eso.org)? If so, explain the need for new data.

We could find no spectro-photometric secondary eclipse data of WASP-121b in the ESO archive.

9b. GTO/Public Survey Duplications:

10. Applicant's publications related to the subject of this application during the last 2 years

Gibson et al. 2017, MNRAS, *accepted*: VLT/FORS2 comparative transmission spectroscopy II: confirmation of a cloud-deck and Rayleigh scattering in WASP-31b, but no potassium?

Armstrong, De Mooij et al. 2017, Nature Astronomy, 1, 4: Variability in the atmosphere of the hot giant planet HAT-P-7 b

Thompson, Watson, De Mooij & Jess 2017, MNRAS, *accepted*: The Changing Face of α Centauri B: Probing plage and stellar activity in K-dwarfs

Cegla, Lovis, Bourrier, Watson & Wyttenbach 2017, A&A, 598, L3: A cautionary tale: limitations of a brightness-based spectroscopic approach to chromatic exoplanet radii

Nikolov, Sing, Gibson et al. 2016, ApJ, 832, 191: VLT FORS2 Comparative Transmission Spectroscopy: Detection of Na in the Atmosphere of WASP-39b from the Ground

Evans, Sing, Wakeford, Nikolov, Ballester, Drummond, Kataria, Gibson et al. 2016, ApJ, 822, L4: Detection of H2O and Evidence for TiO/VO in an Ultra-hot Exoplanet Atmosphere

Gettel et al. 2016, ApJ, 816, 95: The Kepler-454 System: A Small, Not-rocky Inner Planet, a Jovian World, and a Distant Companion

Cegla, Oshagh, Watson et al. 2016, ApJ, 819, 67: Modeling the Rossiter-McLaughlin Effect: Impact of the Convective Center-to-limb Variations in the Stellar Photosphere
Sedaghati et al. 2015, A&A, 576, L11: Regaining the FORS: optical ground-based transmission spectroscopy of the exoplanet WASP-19b with VLT+FORS2

Burton, Watson et al. 2015, MNRAS, 446, 1071: Defocused transmission spectroscopy: a potential detection of sodium in the atmosphere of WASP-12b

Esteves, De Mooij et al. 2015, ApJ, 804, 150: Changing Phases of Alien Worlds: Probing Atmospheres of Kepler Planets with High-precision Photometry

11. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info	Reference star
A	WASP-121	07 10 24	-39 05 51	12.0	10.44			

Target Notes: WASP-121 has at least three suitable comparison stars of similar brightness within the field-of-view of VLT/FORS2.

12. Scheduling requirements

This proposal involves time-critical observations, or observations to be performed at specific time intervals.

12. Scheduling requirements contd...

4. Specific date(s) for time critical observations:

Run	from	to	reason
A	17-nov-17	17-nov-17	WASP-121b secondary eclipse visible.
A	01-dec-17	01-dec-17	WASP-121b secondary eclipse visible.
A	10-dec-17	10-dec-17	WASP-121b secondary eclipse visible.
A	24-dec-17	24-dec-17	WASP-121b secondary eclipse visible.
A	02-jan-18	02-jan-18	WASP-121b secondary eclipse visible.
A	07-jan-18	07-jan-18	WASP-121b secondary eclipse visible.
A	16-jan-18	16-jan-18	WASP-121b secondary eclipse visible.
A	21-jan-18	21-jan-18	WASP-121b secondary eclipse visible.
A	30-jan-18	30-jan-18	WASP-121b secondary eclipse visible.
A	13-feb-18	13-feb-18	WASP-121b secondary eclipse visible.
A	22-feb-18	22-feb-18	WASP-121b secondary eclipse visible.
A	08-mar-18	08-mar-18	WASP-121b secondary eclipse visible.

13. Instrument configuration

Period	Instrument	Run ID	Parameter	Value or list
100	FORS2	A	Detector	MIT
100	FORS2	A	MOS	600z+OG590

6b. Co-investigators:

...continued from Box 6a.

R.	Booth	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK