European Organisation for Astronomical Research in the Southern Hemisphere

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APPLICATION FOR OBSERVING TIME

PERIOD: **102A**

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**

Excursions into inversions: the search for TiO and VO in the WASP-121b dayside

2. Abstract / Total Time Requested

Total Amount of Time: 2 nights VM, 0 hours SM

In recent years, WASP-121b has emerged as one of the best targets to observe various atmospheric phenomena in hot Jupiters. Whilst a recent study presented compelling evidence of a stratosphere in WASP-121b, a robust, dayside detection of TiO and VO – compounds thought to give rise to such an inversion later – has so far proved elusive. We propose to use differential spectro-photometry to observe two secondary eclipses of WASP-121b with FORS2 in the wavelength range 737 - 1070 nm. This window is dominated by TiO and VO features and will yield an unambiguous detection if they are present. This will be the first robust detection of TiO and VO in an exoplanet's emission spectrum, which will allow us to discriminate between competing theories regarding the formation of stratospheres in these extreme conditions. This will also be the first time that any telescope has used spectro-photometry to observe exoplanetary secondary eclipses at these wavelengths.

3.

Run	Period	Instrument	Time	Month	Moon	Seeing	Sky	Mode	Type
A	102	FORS2	2n	jan	g	n	THN	v	

4. Number of nights/hours

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-hour observations 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:

Matthew Hooton, mhooton01@qub.ac.uk, UK, Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast

6a. Co-investigators:

N.P.	Gibson	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK
C.A.	Watson	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: *This is a resubmission of 0100.C-0723. The OPC's comments have been taken into consideration.* Since the initial detections of thermal emission from hot Jupiters, many attempts have been made to search for stratospheres (i.e. inversion layers, where atmospheric temperatures increase with height). The signatures for stratospheres are found in a planet's emission spectrum, where molecular features are visible in emission rather than absorption. Burrows et al. (2007) showed that the emission measurements of HD 209459b were better fit by models with stratospheres than those without. Stratospheres were soon reported to have been observed in the atmospheres of HD 149026b and TrES-2b. However, more recent data have cast doubt on these initial detections, with new models without a stratosphere fitting measurements of thermal emission just as well as those with a stratosphere (e.g. Line et al. 2016). More recently, Haynes et al. (2015) suggested the presence of a stratosphere in the the atmosphere of WASP-33b. However, the fact that WASP-33 is a delta-scuti variable makes data analysis and interpretation extremely challenging.

Running parallel to this, theorists and modellers have proposed the conditions that could give rise to stratospheres in these extreme environments. Hubeny et al. (2003) predicted that strongly absorbing compounds TiO and VO could be present in the atmospheres of hot Jupiters, which would likely give rise to stratospheres. Fortney et al. (2008) proposed that TiO and VO, and consequently stratospheres, would only be present in the atmospheres of the most highly irradiated hot Jupiters. However, Spiegel et al. (2009) and Showman et al. (2009) suggest that condensation in cold traps could remove TiO and VO from the gas phase, even in hotter planets. Furthermore, 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 the planet's ability to host a stratosphere. Despite the importance of TiO and VO, only recently Sedaghati, Gibson et al. (2017) used FORS2 to observe the transmission spectrum of WASP-19b and reported a detection of TiO (see Fig. 1)– to date the only robust detection of TiO and VO in a planet's terminator.

WASP-121b is a hot Jupiter whose 1.27 day period puts it close to being tidally disrupted. The combination of its small orbital separation, its hot F6V-type host star and its inflated size gives it almost unparalleled suitability for atmospheric study using observations of its transmission and emission spectra. Delrez et al. (2016) measured a photometric z'-band eclipse depth of 603 ppm – one of the few cases where thermal emission is detectable in this window (e.g. Burton, Watson, Gibson et al. 2012, Föhring et al. 2013). Evans, Gibson et al. (2016) found that their HST/WFC3 transmission spectroscopy data of WASP-121b was best fit with an atmospheric model including TiO and VO. Later, Evans et al. (2017) observed secondary eclipses of WASP-121b with HST/WFC3 in wavelength range 1.1-1.7 μm and reported the detection of a stratosphere on the basis of water features detected in emission, and a tentative detection of a VO feature (see. Fig 1). Robust detection of TiO and VO in the atmosphere of WASP-121b, or in the emission spectrum of any planet, has so far proven elusive.

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 737 - 1070 nm. 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. Unlike the redder wavelength range probed by Evans et al. (2016, 2017), this range will be dominated by TiO and VO features if they are present, which will allow a $>5\sigma$ detection if TiO and VO are present in the upper atmosphere. The detection of a stratosphere reported by Evans et al. (2017) will be confirmed by whether the spectral features in this range are in emission. *This would be the first robust detection of TiO and VO in the atmosphere of WASP-121b, as well as the first robust detection of TiO and VO in an exoplanet's emission spectrum. It will allow us to discriminate between competing theories regarding the conditions in which stratospheres arise.*

These observations will be utilising the technique of differential spectro-photometry. Each of the time-series spectra is divided into distinct wavelength channels, allowing features associated with specific molecules to be identified. This is a very efficient way to collect data compared to broadband photometry, given that for most photometric instruments any given eclipse can only be observed with one filter at a time. 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. 2014) and FORS2 (Nikolov et al. 2016, Gibson et al. 2017) 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. *This observation 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 in this window.*

These observations will strongly constrain the planet's SED and are therefore also valuable in the absence of TiO. As our team has already conducted z'-band eclipse measurements for WASP-19b and WASP-103b (in preparation), we will be able to make a direct comparison of the inferred atmospheric properties for these planets. This will enable any common features to be identified for this extreme class of gas-giant, and constrain the C/O classification scheme for hot Jupiter atmospheres. We will also be able to identify water absorption

7. Description of the proposed programme and attachments

Description of the proposed programme (continued)

features in this window. This group has a solid track record in secondary eclipse studies at these wavelengths. Indeed, the z'-band eclipse measurement of WASP-19b 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, 2012).

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 lightcurves of the comparison stars are used to correct the lightcurves of the target star in each wavelength bin. This produces high precision eclipse lightcurves 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 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 901 nm, giving a wavelength coverage of $\approx$ 737-1070 nm. 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.

To interpret the spectrum, we will perform a retrieval analysis to constrain the T-P profile and chemical species present in the atmosphere. In our retrieval, we will allow the abundances of species including H_2O, TiO, VO, FeH, CrH, CO, CH_4 and NH_3 to vary as free parameters, and assume that these gases are vertically well-mixed throughout a hydrogen-dominated atmosphere. We will adopt a one-dimensional analytic formulation for the T-P profile, which assumes radiative equilibrium and is flexible enough to describe atmospheres with and without stratospheres. This will allow us to calculate the brightness temperature for altitudes probed by each wavelength bin, identify the spectral features present in this window and identify the presence of any stratosphere.

Attachments (Figures)

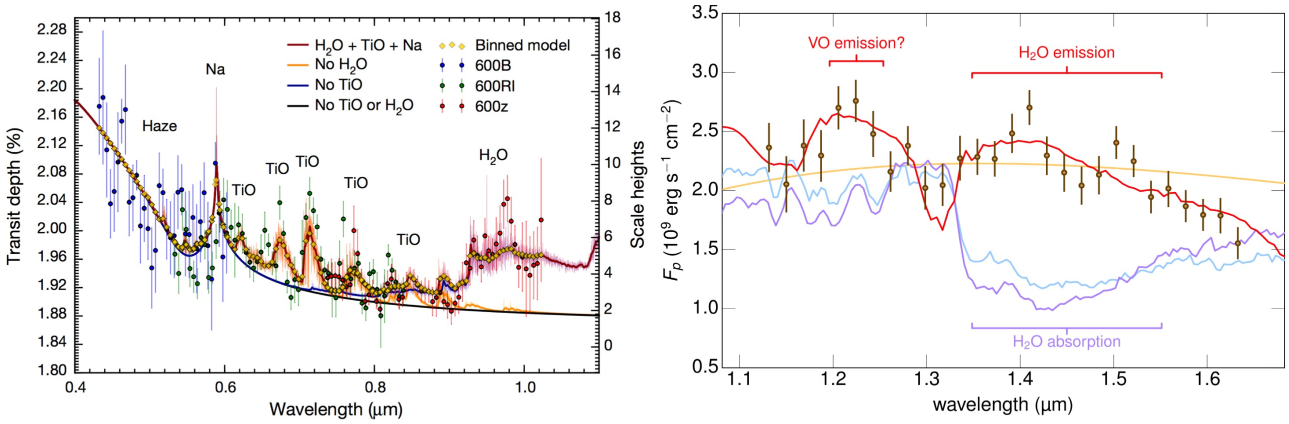

Fig. 1- Left: FORS2 transmission spectrum of WASP-19b (Sedaghati, Gibson et al., 2017), achieving typical precision of $\sim 10^{-4}$ in the transit depth in $\sim$ 10 nm bins. TiO features are detected at 7.7σ, demonstrating the ability of FORS2 to perform such a study. Right: HST/WFC3 emission spectrum of WASP-121b (Evans et al. 2017). Water features are visible in emission, demonstrating the presence of a stratosphere. A VO feature is tentatively reported. Our proposal is to use FORS2 to perform a similar observation, but at wavelengths 737-1070 nm – a window in which TiO and VO features are much more prominent (see left-hand panel).

References: Burrows et al. (2007), ApJ, 668, L171; Burton, Watson, Gibson et al. 2012, ApJS, 201, 36; Delrez et al. 2016, MNRAS, 458, 4025; Evans, Gibson et al. 2016, ApJ, 822, L4; Evans et al. 2017, Nature, 548, 58; Föhring et al. 2013, MNRAS, 435, 2268; Fortney et al., (2008), ApJ, 678, 1419 Gibson et al. (2013), MNRAS, 436, 2974; Gibson et al. 2017, MNRAS, 467, 4591; Haynes et al. 2015, ApJ, 806, 146; Hubeny et al. 2003, ApJ, 594, 1011; Kriedberg et al. 2014, Nature, 505, 69; 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; Sedaghati, Gibson et al. (2017), Nature, 549, 238; Showman et al. (2009), ApJ, 699, 5645; Spiegel et al. (2009), ApJ, 699, 1487

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 request nights at which the target is more than 50° from the Moon. Note that all secondary eclipses for this planets listed in Sect. 12 have been checked to have a larger moon distance.

Time Justification: (including seeing overhead) We request a total of 12 hours to observe two secondary eclipses of WASP-121b for 6 hours each. The 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 requires 6 hours of observing time per eclipse, including overheads. Given that ultra-high precision spectro-photometric 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 (e.g. Burton, Watson, Gibson et al. 2012), 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 per spectral pixel around the central wavelength. By combining all the in-eclipse frames, the expected S/N per pixel will be 4800, which can be further increased by binning the spectra in the wavelength direction. Even binning by 10 pixels, we will be able to detect the thermal emission in the individual wavelength bins.

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. However, as it is essential to demonstrate that any detection of a TiO/VO is robust (especially in light of earlier controversies), 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-Is Gibson and De Mooij–also Co-Is 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 our published FORS2 transmission spectroscopy data (e.g. Gibson et al. 2017), 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):

Due to the difficulties with scheduling our request of 2x6 hour observing blocks on separate nights in service mode, we request visitor mode for these observations, perhaps changing to delegated visitor mode for the second observing block.

8c. Calibration Request:

Standard Calibration

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

100.C-0662(A) Characterising the material around the young exoplanet β Pictoris b PI: De Mooij. ToO observations to observe any transiting material during P100, no observations triggered to date.
099.C-0763: *Peeking above the clouds: exoplanet atmospheres at high spectral resolution with UVES.* Gibson, De Mooij, Watson et al.
099.C-738: Characterising the material around the young exoplanet β Pictoris b PI: De Mooij. ToO observations to observe any transiting material during P99, no observations triggered
599.C-0751: *Characterising the material around the young exoplanet beta Pictoris b* De Mooij, Hooton, Watson, Gibson, Thompson, et al. Monitoring program with VLT/UVES during P99/P100 to search for transiting material at high spectral resolution. Observations started in April 2017. Observations ongoing (Carry-over into P101), variations in Ca II detected, but no signals from rings. Analysis of gas-absorption in progress.
098.C-0547: *Solving the TiO mystery in hot exoplanets: high-resolution transmission spectroscopy of WASP-121b.* Gibson, De Mooij, Watson et al.

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.

There is 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

Sedaghati, Gibson et al. 2017, Nature, 549, 238: Detection of titanium oxide in the atmosphere of a hot Jupiter.

De Mooij, Watson & Kenworthy 2017, MNRAS, 427, 2713: Characterizing exo-ring systems around fast-rotating stars using the Rossiter–McLaughlin effect.

Gibson et al. 2017, MNRAS, 467, 4591: 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

Mackebrandt, Gibson et al. 2017, A&A, 608, A26: Transmission spectroscopy of the hot Jupiter TrES-3 b: Disproof of an overly large Rayleigh-like feature
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

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.

We note that the observations are time critical, as they must coincide with a secondary eclipse with suitable visibility. Unfortunately, the TimeCritical automated checks will not allow a single night on which the secondary eclipse occurs to be specified (as we are asking for 2 separate nights). They are therefore listed here, with the dates indicating the **Chilean date at the start of the night** that suitable secondary eclipses of WASP-121b are visible:

23-nov-18; 07-dec-18; 16-dec-18; 25-dec-18; 30-dec-18; 08-jan-19; 13-jan-19; 22-jan-19; 27-jan-19; 05-feb-19; 14-feb-19; 28-feb-19; 23-mar-19

12. Scheduling requirements

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

13. Instrument configuration

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

6b. Co-investigators:

...continued from Box 6a.

S.	Merritt	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK
J.	Costes	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK
J.	Wilson	Astrophysics Research Centre,Department of Physics and Astronomy,Queen's University Belfast,UK