TAG: PATT

LIVERPOOL TELESCOPE
APPLICATION FOR TELESCOPE TIME

Ref: PL/18A/xxx

Semester: 18A **Duration (Semesters):** 1 **PROGID:**

Applicants (PI First)	Institution	email
Matthew Hooton	**QUB**	**mhooton01@qub.ac.uk**
Chris Watson	Queen's University Belfast	c.a.watson@qub.ac.uk
Ernst de Mooij	Dublin City University	ernst.demooij@dcu.ie
Neale Gibson	Queen's University Belfast	n.gibson@qub.ac.uk
Andrew Thompson	Queen's University Belfast	athompson1501@qub.ac.uk
Stephanie Merritt	Queen's University Belfast	smerritt01@qub.ac.uk

⊗ Data are to be used in a PhD thesis of: Matthew Hooton - QUB

Title: Excursions into inversions: the first detection of planetary thermal emission in the i'-band

Abstract:
The hot Jupiter WASP-12b has a dayside temperature of over 3,000 K, making it one of the hottest-known exoplanets. The combination of its small orbital separation and its bright host star makes it a terrific candidate for atmospheric categorisation. We propose to use IO:O to measure secondary eclipses of WASP-12b in the i'-band - a good discriminator between many thermal emission models for which to date there are no published results. This will allow us to place important constraints on the atmospheric composition of WASP-12b and provide information on its temperature-pressure profile. The combination of these measurements and those from a previous observation taken with INT/WFC would constitute the first-ever robust detection of planetary thermal emission in the i'-band, as well as the shortest-wavelength ground-based robust detection of a secondary eclipse of an exoplanet.

TIME REQUESTED

This semester (hours): 12 **Total (hours):**

Min. Useable %: 50

Jan ⊗ Feb ⊗ Mar ○ Apr ○ May ○ Jun ○ Jul ○ Aug ○ Sep ○ Oct ○ Nov ○ Dec ○

SCHEDULING CONSTRAINTS

Timing:	PHASED	**Group Cadence (days):**	1
ToO:		**ToO Likelihood (%):**	
Seeing (arcsec):	4	**Sky Brightness:**	6
Photometric:	Y		

INSTRUMENTS

IO:O	⊗	**Filters**	SDSS-i
IO:I	○	**Filters**	
RINGO3	○		
RISE	○		
SPRAT	○		
FRODOSpec	○	**Gratings**	
Other*			

Always consult the Call for Proposals and LT web-pages before applying to use ANY instrument.

ltpattv0p7.sty - 0123456789

Summary of progress on previous, related LT Programmes:

PROPID	Alloc.	Rank	Used	Comments
PL16A10	14.5	B	14.5	*Analysis in progress.*

List of previous related and unrelated LT Publications:

Details of related/complementary proposals to this or other facilities:

TARGET LIST:

WASP-12 - RA 06 30 33.0; DEC +29 40 20; V_{mag} 11.69

SCIENTIFIC CASE:

Background – Observing a planet during occultation by its host star (a secondary eclipse) is a powerful tool to study the thermal structure of its atmosphere. Measuring the thermal emission as a function of wavelength allows an emission spectrum to be constructed; from this, features such as temperature inversions can be detected. Soon after the initial detections of planetary secondary eclipses, temperature inversions were reported in the atmospheres of numerous hot Jupiters, including HD 209458b (Burrows et al. 2007) and HD 149026b (Harrington et al. 2007). Theories put forward to explain their presence included that of Fortney et al. (2008), who proposed that the temperatures in the upper atmospheres of the most highly-irradiated planets would be sufficiently high to support the presence of the highly-absorbing metal oxides TiO and VO. However, new observations and reanalyses of old data have cast doubt on all of these reported thermal inversions (e.g. Diamond-Lowe et al. 2014, Line et al. 2016), with models without inversions fitting the data as well as those with inversions.

In an emission spectrum, the presence of a temperature inversion can be inferred by spectral features being visible in emission rather than absorption. In August, Evans et al. (2017) reported a 5σ detection of a temperature inversion in the atmosphere of the hot Jupiter WASP-121b ($T_{dayside}$ $\sim$2700 K), on the basis of a detected water feature in emission – the first detection of any spectral features in emission for an exoplanet. They also reported evidence of VO emission features: this molecule is potentially responsible for such inversions. If Fortney's theory is true, we would expect inversion-causing metal oxides to be present in planetary atmospheres at and above this temperature.

The extremely hot Jupiter WASP-12b – The highly-irradiated planet WASP-12b orbits its host star in just over 1 day. Due to the high incident flux, the day-side temperature is expected to reach $\sim$3000K. Crossfield et al. (2012) show that the planet's SED could be approximated with an isothermal model of $\sim$3000K. However, Föhring et al. (2013) find that the planet's emission spectrum could be better fit with an atmospheric model that is carbon-rich, which is also supported by Stevenson et al. (2014). Interestingly, the z-band measurement from Föhring et al. (2013) is discrepant by $\sim 3\sigma$ compared to the measurement from Lopez-Morales et al. (2010), (see the data points in Fig. 1, right panel). This could be due to either systematic effects in the data (e.g. from the instrument), or caused by weather on the planet. It should be noted that the best-fit model from Stevenson et al. (2014) is unable to fit the measurements from Föhring et al. (2013).

Objectives – We propose to measure the i'-band secondary eclipse depth of WASP-12b using IO:O. As i'-band observations 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-12b 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 – 11000Å, observable as a decrease in flux in the i'- and z'-bands (see Fig. 2). If the planet has a high C/O ratio, however, then TiO and VO are depleted and thus there is not significant absorption in the i'- and z'-bands and the resulting thermal emission is much stronger at those wavelengths. WASP-12b 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 becomes measurable with current technology.

Whilst there have been numerous robust detections of planetary thermal emission in the z'-band, there have so far been none at i'-band or shorter. This is due to the typically tiny signal sizes present at these wavelengths, despite the wealth of complementary information such observations would provide. In the past we have observed one i'-band secondary eclipse of WASP-12b using INT/WFC, in which we appear to be able to detect a 0.99 mmag signal (see Fig. 1, left panel). This is a notable result in its own right: however, due to the well-documented discrepancies in past reported eclipse depths it is sensible to confirm this detection by repeating this observation. Therefore, we request to use the IO:O camera on the LT to observe two i'-band secondary eclipses in order for us to acquire a detection of this signal. *The combination of these measurements would constitute the first ever robust detection of planetary thermal emission in the i'-band, as well as the shortest-wavelength ground-based robust detection of a secondary eclipse of an exoplanet.*

TECHNICAL CASE:

We request a total of 12 hours (six hours per eclipse) of observing time with IO:O at the LT. Based on our INT observation, the expected eclipse depth is around 1 mmag in the i'-band, well within range of LT (e.g. Fig. 1, left panel).

These observations require a very high precision in order to detect the small signal from the planet. To achieve this, we will disignificantly defocus the telescope to 4" and observe the target in staring mode. In doing so, the flux from the target is spread over a greater number of pixels, allowing longer exposures to be taken while keeping the flux in the linear regime of the detector. Spreading the light over many pixels also reduces the impact of any residual pixel-to-pixel variations not removed by the flat-field, which in turn improves the stability of the lightcurve. We will also keep the target at the same position on the detector for the entirety of the observations, in doing so improving the stability of the lightcurve further. The use of staring mode will increase the efficiency of the observations, as no telescope moves have to be performed. It is also worth noting that these observations are not photon-noise limited, and that since we are measuring the secondary eclipse, stellar activity (e.g. starspots), will not impact these observations.

We will use 2x2 binning and set the exposure time to 40 seconds. In addition, we will also observe a long out-of-eclipse baseline, as this sets the reference level with respect to which the eclipse is measured, and will also allow us to characterise and correct systematic effects. Per exposure, we expect to achieve a SNR of $\sim$1500. Taking into account all overheads, we will be able to obtain $\sim$180 frames during the eclipse, resulting in theoretical 5σ detection limits of $>$240 ppm (0.24 mmag) which would result in a 20σ detection of the signal seen with the INT.

We request two secondary eclipse observations to help better calibrate the systematics that will be the dominant source of error in this study. We also require $\sim$3 hours of contemporary out-of-eclipse light each night to help detrending – a total of 6 hours per eclipse (the eclipse duration is 180 minutes). For each set of six hours, we request that the eclipse falls in the middle of this time, with minimum 30 minutes (preferred minimum 45 minutes) of baseline before and after the eclipse. We note, however, that an award of one eclipse would still be of use to us.

Target observability and scheduling constraints

Below we give the dates on which a secondary eclipse of WASP-12b is visible from La Palma. WASP-12 passes within a degree of zenith, so we have taken care to ensure the eclipses occur at times where they will be fully outside the zenith avoidance zone of the LT. Note that these dates are for the start of the night.

January 6, 8 & 20
February 13

FIGURES AND TABLES:

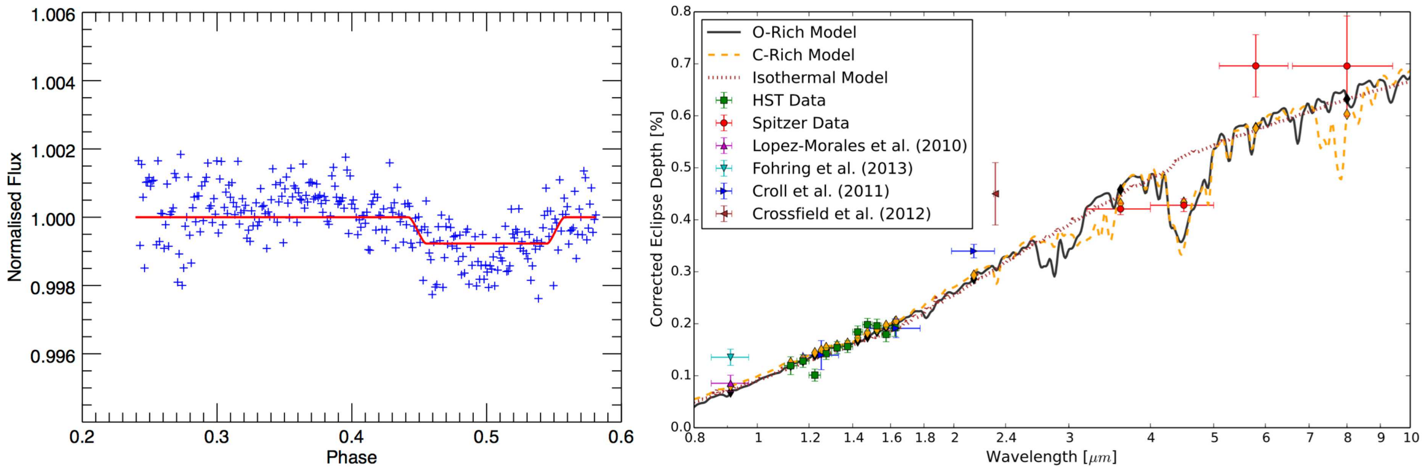

Figure 1: Left panel: i'-band secondary eclipse of WASP-12b taken with INT/WFC, fit using MCMC with an eclipse depth of 0.99±0.16 mmag at 2.8σ significance. Whilst this is a convincing detection of i'-band thermal emission from WASP-12b, it is advisable to take repeat measurements to confirm the reliability of any detected signal. We note discrepancies in measured eclipse depths at longer wavelengths than i'-band (e.g. Lopez-Morales et al. 2010, Föhring et al. 2013, both shown in the right panel). Right panel: Emission spectrum for WASP-12b with three different atmospheric models overplotted, taken from Stevenson et al. (2014). This observation would enable us to confirm detected thermal emission at wavelengths shorter than any previously measured for WASP-12b.

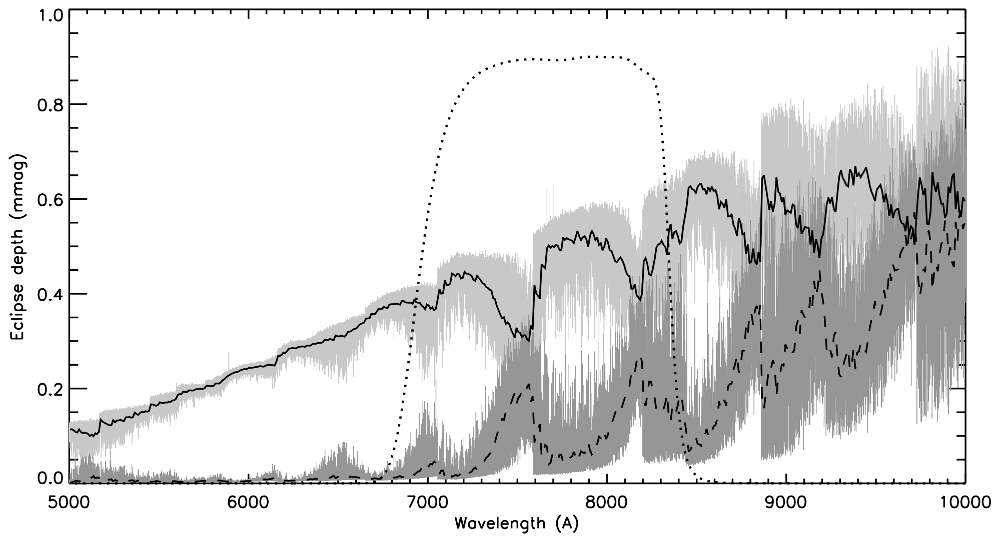

Figure 2: Model for the emission spectrum for the hot Jupiter WASP-33b for a TiO rich atmosphere. The light grey model is for an inversion layer and the dark grey is for a non-inverted model. The response function of the SDSS i'-filter has been overplotted, as a demonstration of how sensitive a secondary eclipse measurement in at wavelengths is to TiO emission/absorption. We note that this diagram is for illustrative purposes only; WASP-12b is marginally cooler but should have deeper eclipses than WASP-33b.

References:

Burrows et al. 2007, ApJL, 668, L171;
Burton, Watson, Gibson et al. 2012, ApJS, 201, 36
Crossfield et al. 2012, ApJ 760, 140;
Diamond-Lowe et al., 2014, ApJ, 796, 66
Evans et al. 2017, Nature, 548, 58;
Föhring et al. 2013, MNRAS 435,2268;
Fortney et al. 2008, ApJ, 678, 1419
Harrington et al. 2007, Nature, 447, 691
Line et al., 2016 AJ, 152, 203
Lopez-Morales et al. 2010, ApJL 716, 36
Madhusudhan 2012, ApJ, 758, 36
Stevenson et al. 2014, ApJ 791, 35