TAG: PATT

LIVERPOOL TELESCOPE
APPLICATION FOR TELESCOPE TIME

Ref: PL/19A/xxx

Semester: 19A **Duration (Semesters):** 1 **PROGID:**

Applicants (PI First)	Institution	email
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◯ Data are to be used in a PhD thesis of:

Title: Storms or Systematics? Investigating the changing eclipse depth of hot Jupiter WASP-12b

Abstract:
Secondary eclipse observations are important tools to study hot Jupiters. However, many such observations have shown considerable disagreement in their eclipse depths, which inhibits our ability to draw reliable conclusions based on these data. These disagreements could be due to systematic errors associated with differences in instrumentation, telescopes and methods of reduction and analysis. Alternatively, they could be due to the thermal emission from these exoplanets varying in time. We propose to use the LT/IO:O to observe four z-band secondary eclipses of WASP-12b during January. We have already been awarded time for this on the INT and will observe the same eclipses simultaneously with both telescopes to discriminate between the described scenarios. A successful distinction will be highly influential for exoplanet research, and could potentially provide the second confirmed detection of atmospheric variability in an exoplanet.

TIME REQUESTED

This semester (hours): 24 **Total (hours):**

Min. Useable %: 50

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

SCHEDULING CONSTRAINTS

Timing:	FIXED	**Group Cadence (days):**	
ToO:	N	**ToO Likelihood (%):**	
Seeing (arcsec):	4	**Sky Brightness:**	10mag
Photometric:	N		

INSTRUMENTS

IO:O	⊗	**Filters**	SDSS-z
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.

Summary of progress on previous, related LT Programmes:

PROPID	Alloc.	Rank	Used	Comments
PL18A10	12	B	12	*6 hours useful data. MNRAS publication in preparation.*
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:

This proposal is part of a multi-telescope programme to simultaneously observe secondary eclipses of WASP-12b. We have already been awarded time on the Isaac Newton Telescope (INT) for the 7 nights in January that secondary eclipses of WASP-12b are visible from La Palma. Our plan is to simultaneously observe these secondary eclipses of WASP-12b using the INT and at least one other telescope. We have submitted another proposal to the Aristarchos Telescope in Greece for the nights where complete secondary eclipses are observable during January from both Aristarchos and La Palma. The eclipses we will observe with the LT are those that are visible from La Palma but that occur at times when WASP-12 is outside the zenith avoidance zone of the LT, and are largely different to the nights we will observe with Aristarchos. Therefore, our plan of using three telescopes will ensure that at least two telescopes are observing each eclipse in January. This is most effective method of detecting any time-dependent changes in the thermal emission properties of the WASP-12b dayside atmosphere that occur throughout the month. In the event that our Aristarchos proposal is unsuccessful, we note that the ability to observe the four eclipses simultaneously with the LT and INT will still be sufficient to complete our science goals of spotting any differences in systematic errors, and monitoring variability through the month. Hence, we write this proposal assuming we only have the time on the INT to supplement this proposal for LT time.

TARGET LIST:

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

SCIENTIFIC CASE:

Background – Research into exoplanet atmospheres is a field of intense activity. Secondary eclipse observations (when the planet passes behind its host star) allow the thermal emission properties in the daysides of exoplanets to be measured. Such studies not only allow the planetary dayside temperature and heat redistribution efficiency to be estimated (e.g. Knutson et al. 2007), but also allow planetary atmospheric properties to be constrained.

To date, the vast majority of secondary eclipse studies have been conducted at wavelengths of 1.1 μm and longer, as few exoplanets produce a sufficiently large signal to be detectable at shorter wavelengths. For the ones that do, secondary eclipse observations in the red optical (wavelengths of 700-1100 nm, in rough alignment with the i- and z-bands) yield important information about the composition and structure of their atmospheres. In particular, the i- and z-bands contain prominent TiO and VO features, which are highly-absorbing compounds expected to give rise to temperature inversions if present in appreciable quantities in the upper atmospheres of hot Jupiters (e.g. Hubeny et al. 2003, Fortney et al. 2008). However, the two planets for which multiple z-band eclipse observations have been conducted both show considerable discrepancies in the reported depths. Burton et al. (2012; featuring two members of our team) reported a depth of 0.88$\pm$0.19 mmag for WASP-19b, which is significantly deeper than the 0.35$\pm$0.11 mmag depth reported by Lendl et al. (2013). WASP-12b also shows considerable disagreement, with reported depths of 0.82$\pm$0.15 mmag (López-Morales et al. (2010) and 1.30$\pm$0.13 mmag (Föhring et al. 2013).

In the 2018A semester, we successfully proposed to use the LT/IO:O to observe two secondary eclipses of WASP-12b in the i-band (ID: PL18A05), to confirm a detection of depth 0.99$\pm$0.16 mmag we had observed using the Isaac Newton Telescope (INT) a year earlier. One of our observations was lost to a fault with the Cassegrain rotator. The other observation suffered from poor seeing, yet we were able to detect a depth of 0.49$\pm$0.24 mmag (Hooton et al., in prep.; see Fig 1), demonstrating the suitability of the LT/IO:O to perform such a study. This result, which disagreed with our INT detection by $>2\sigma$, will be submitted for publication in the coming weeks.

All of the results described above are part of a wider picture of disagreement in observations designed to classify the atmospheres of exoplanets, where high-significance detections are reported, both during transit and eclipse using both photometry and spectroscopy, only for new observations to routinely contradict these findings (e.g. Todorov et al. 2010, De Mooij et al. 2011 for HAT-P-1b in emission; Sing et al. 2016, Gibson et al. 2017 for WASP-31b in transmission). Without understanding the source of these disagreements, it is difficult to reliably constrain the temperatures, compositions and structures of the atmospheres of these exoplanets.

Objectives – This proposal will determine the cause of the variable secondary eclipse depths reported in the red-optical, which may arise for 2 main reasons. The first is that the differences in the telescopes, instrumentation and data analysis methods used to conduct these studies introduce large systematic errors into the results—if so, it is important that the root cause is identified given the clear impact this has on our ability to probe exoplanet atmospheres. The second is that the time of the observations are different. Föhring et al. (2013) suggested that differences seen in WASP-12b may be due to local variations in the surface brightness of the dayside atmosphere due to storms. Indeed, storms covering 10-20% of the planet surface that are only a few 100K hotter than the 3000K background temperature are adequate to explain the differences. The idea that atmospheric variability is responsible for the differences was afforded greater credence after Armstrong et al. (2016) identified variations in Kepler phase curves of the giant planet HAT-P-7b over timescales of roughly a month (see Fig. 2).

We propose to use the LT to observe four z-band secondary eclipses of WASP-12b during the month of January as part of a unique, multi-telescope campaign to establish the reasons for the disagreements in measured eclipse depths. For all of the four secondary eclipses we propose to observe, we have already been awarded time to carry out near-identical observations using the INT. The ability to observe the same secondary eclipses of an exoplanet with two telescopes at once will allow us to test whether the disagreements are due to systematic errors associated with instrumentation and observing conditions. If we observe similar depths for individual eclipses with the two telescopes, our strategy of observing multiple WASP-12b eclipses over the course of a month will also allow us to search for the changing thermal properties proposed by Föhring et al. (2013), assuming similar variability timescales as those observed by Armstrong et al. (2016) for HAT-P-7b.

A successful distinction between the storm and systematic hypotheses will be highly influential in observational exoplanet research. If the disagreements are due to systematics, this will call into question the very technique of ground-based eclipse observation and will throw the validity of over a hundred reported eclipse depths into doubt. If the disagreements are due to storms, this will provide the confirmation of atmospheric variability for a second exoplanet and encourage searches for atmospheric variability in exoplanets to be routinely conducted.

TECHNICAL CASE:

We request a total of 24 hours (six hours per eclipse) of observing time with IO:O on the LT. We will follow an identical strategy to our 2018A semester LT observation of WASP-12b secondary eclipses, except using the z'-band filter rather than the i'-band filter. Based on previous observations by López-Morales et al. (2010) and Föhring et al. (2013), we expect the eclipse depths of WASP-12b to be in the region of 0.8-1.3 mmag.

These observations require a very high precision in order to detect the small signal from the planet. To achieve this, we will significantly 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 35 seconds. As well as the 3.0 hours of observing time when WASP-12b is during its secondary eclipse, we will also observe $\sim$3 hours of contemporary out-of-eclipse light, 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. From our 2018A observation, on a night which suffered from poor seeing conditions, we achieved a SNR of $\sim$310 per frame. With more typical seeing conditions, a realistic SNR we can achieve is 500 per frame. Taking into account all overheads, we will be able to obtain $\sim$202 frames during the eclipse, resulting in theoretical 5σ detection limits of 0.71 mmag. Given the depths of 0.82 & 1.30 mmag previously measured, we would expect to detect the secondary eclipses of WASP-12b with $>5\sigma$ significance.

The observing team

Our team brings together significant experience of conducting observations of high-precision secondary eclipse photometry and bringing it to publish. MH leads the QUB secondary eclipse campaign to categorise the atmospheres of hot Jupiters at optical and UV wavelengths, for which the initial results are just coming to publication (Hooton et al., submitted to ApJL). CW was part of the team to conduct the first z-band eclipse observation of WASP-19b (Burton et al. 2012): only the third secondary eclipse observation of any exoplanet in the z-band. EdM led the team that published the first ever ground-based detection of the secondary eclipse of an exoplanet (De Mooij & Snellen 2009). NG led the team that published the first secondary eclipse observation of WASP-19b.

Target observability and scheduling constraints

WASP-12 passes within a degree of zenith, so we need to observe eclipses that occur at times when WASP-12 is outside the zenith avoidance zone of the LT. All the nights which fulfil these requirements are listed below. For the four nights in January, we have already been scheduled observing time on the INT, so the ability to observe simultaneously with the LT will allow us to complete our primary science goals. If any of these nights are lost due to weather, then the ability to observe on the listed February/March nights would still allow us to observe eclipses, compare them to our other observations and check for variability. The full allocation of 24 hours (6 hours per eclipse) would help us best monitor any variability in the atmosphere of WASP-12b. A minimum allocation of 12 hours to observe two eclipses would be useful for assessing the impact of different systematics between the two telescopes.

As secondary eclipses are time-critical events, we require fixed timing constraints to ensure our observations are carried out uninterrupted at the correct time. Below, we list the dates on which we can observe a secondary eclipse of WASP-12b using the LT. Note that these dates are for the start of the night.

January 11, 13, 23 & 25
February 17
March 1 & 24

FIGURES AND TABLES:

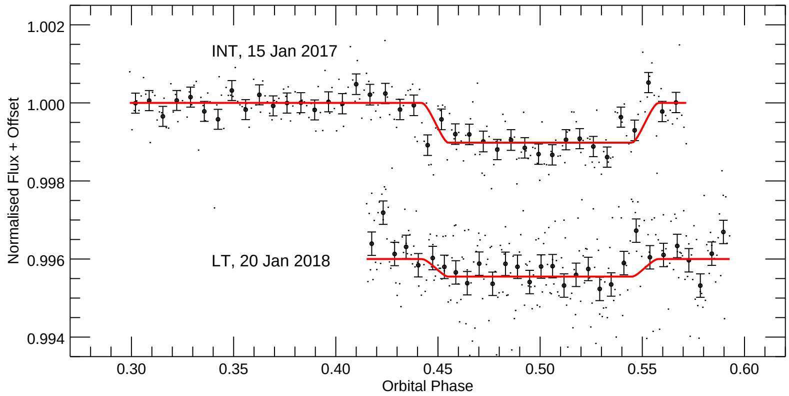

Figure 1: Light curves for i-band secondary eclipses of WASP-12b observed a year apart, taken from Hooton et al. (in prep.). The INT light curve (top) is best fit with an eclipse depth of 0.99±0.16 mmag. The LT light curve (bottom) is best fit with an eclipse depth of 0.49±0.24 mmag. This is just one example the stark contrast between measured eclipse depths in the red-optical. This also demonstrates the ability of 2 metre class telescopes such as LT to perform such a study, as well as this group's ability to observe, reduce and analyse high-precision secondary eclipse photometry.

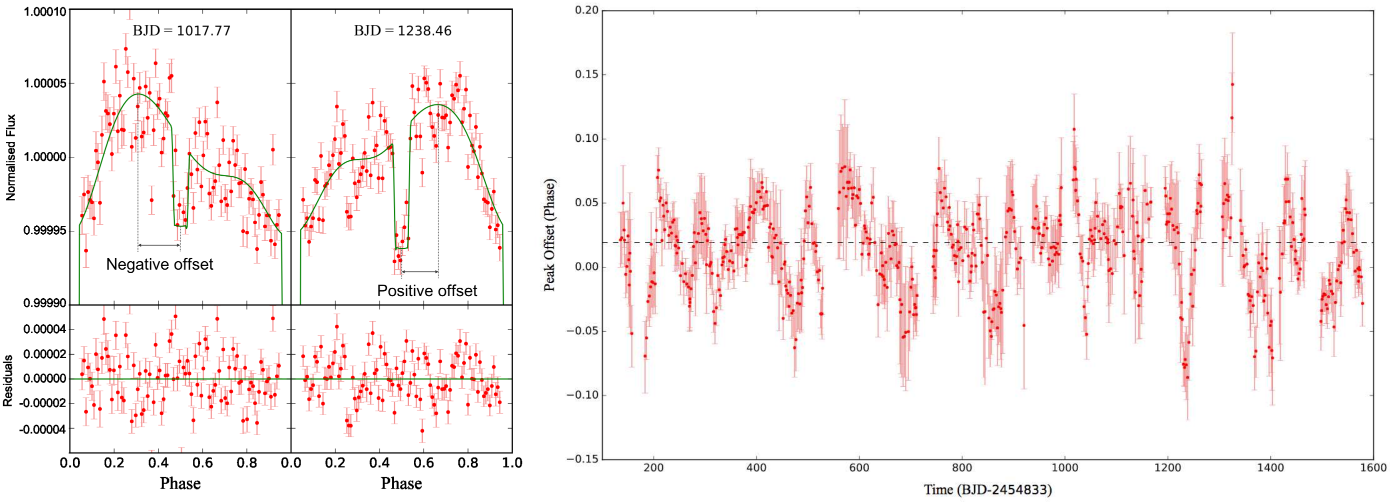

Figure 2: Left: Two selected full-phase curves from four years of Kepler photometry of HAT-P-7b, from Armstrong et al. (2016). In the left panel, the peak flux occurs before the secondary eclipse; in the right panel, the peak flux occurs after the secondary eclipse. Right: The variation in the peak flux offset over the course of the four years, also from Armstrong et al. (2016). The offsets are highly time-correlated and are seen to vary on timescales of roughly a month, which is compelling evidence for atmospheric variability in the dayside atmosphere of HAT-P-7b. Our study will look for changes in the secondary eclipses of WASP-12b over the course of a month.

References:

Armstrong et al. (2016), Nat. Astron, 1, 4;
Burton et al. (2012), ApJS, 201, 36;
De Mooij et al. (2011), A&A, 528, A49;
De Mooij & Snellen (2009), A&A, 493, 35;
Föhring et al. (2013), MNRAS, 435, 2268;
Fortney et al. (2008), ApJ, 678, 1419;
Gibson et al. (2010), MNRAS, 404, L114;
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Hooton et al., MNRAS (in prep.);
Hubeny et al. (2003), ApJ, 594, 1011;
Knutson et al. (2007), Nature, 447, 183;
Lendl et al. (2013), A&A, 552, A2;
Lopez-Morales et al. (2010), ApJL 716, 36;
Sing et al. (2016), Nature, 529, 59;
Todorov et al. (2010), ApJ, 708, 498.