Opticon Proposal

Hooton 2019A/042

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

Semester : 2019A **Science Cat. : exoplanets**

Abstract

Secondary eclipse observations at red-optical wavelengths are important tools to study the atmospheric composition and structure of hot Jupiters. However, past observations of hot Jupiters 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, locations and methods for reduction and analysis. Alternatively, they could be indicative of the thermal emission properties of these exoplanets varying in time. We propose to use the Aristarchos Telescope to observe five z-band secondary eclipses of the hot Jupiter WASP-12b during January. We have already been awarded time on the INT on La Palma for all the requested dates and will observe the same eclipses simultaneously with both telescopes to discriminate between the aforementioned scenarios. A successful distinction will be highly influential for exoplanet research, as it will inform the community's future approach to designing campaigns to observe the atmospheres of hot Jupiters, and potentially provide the second confirmed detection of atmospheric variability in an exoplanet.

Telescopes

Telescope	Observing mode	Instruments
Aristarchos	visitor	LN CCD

Applicants

Name	Affiliation	Email	Country		Potential observer
Matthew Hooton	Queen's University Belfast (Astrophysics Research Centre)	mhooton01@qub.ac.uk	United Kingdom	Pi	Yes
Dr Christopher Watson	Queen's University Belfast (Mathematics and Physics)	c.a.watson@qub.ac.uk	United Kingdom		Yes
Ernst de Mooij	Dublin City University (School of Physical Sciences)	ernst.demooij@dcu.ie	Ireland		Yes
Neale Gibson	Queen's University Belfast	N.Gibson@qub.ac.uk	United Kingdom		Yes
Ruben Asensio-Torres	Stockholm University (Astronomy Department)	ruben.torres@astro.su.se	Sweden		Yes

Applicants are continued on the last page

Contact Author

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Is this a long term proposal: No

Overall scheduling requirements

As we need to observe secondary eclipses of WASP-12b for which we have also been awarded time on the INT as part of our study, we request time on the following nights:

January 1, 11, 12, 23, 24.

Observing runs

run	telescope	instrument	time request (minimal)	moon	weather	mode	seeing	configuration	comments / constraints
A	Aristarchos	LN CCD	5n (3n)	Bright	any	visitor	any	Filter: Stromgren z	Standard configuration. See justification for observing strategy. We request 5 nights of observation on the Aristarchos Telescopes to observe 5 secondary eclipses. We request that these nights are scheduled simultaneous with time we have already been allocated on the INT in order to distinguish between instrumental variations and weather in the exoplanet atmosphere. Below we list the nights on which a secondary eclipse of WASP-12b is visible from Aristachos Telescope and for which we have already been awarded time on the INT. Note that the dates are for the start of the night. January 1, 11, 12, 23, 24.

Targets

Field	RA	Dec	Epoch	Exposure (sec.)	Runs	S/N	Red Magn.	Infrared Magn.	Diameter (arcsec)	Comments
WASP-12	06:30:32.80	+29:40:20.3	J2000	108000	A	1250	11.57	10.188	0	

1 Scientific Rationale

Research into the properties of exoplanet atmospheres is a field of intense activity. Secondary eclipse observations (when the planet passes behind the 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 global 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. 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). Observations of secondary eclipses in the i- and z-bands also allow constraints to be put on the spectral energy distributions of exoplanets at wavelengths shorter than their peak emission, and hence are very sensitive to temperature changes.

Members of this group detected a 0.88$\pm$0.19 mmag z-band secondary eclipse of the exoplanet WASP-19b (Burton et al. 2012), one of the most highly irradiated exoplanets known. This was only the third ever ground-based secondary eclipse detection at such short wavelengths, and Madhusudhan (2012) cited it as a crucially important discrimination in determining WASP-19b's chemical composition. As researchers realised the importance of capturing z-band secondary eclipses, the number of observations around these wavelengths increased, generating curious results. For WASP-19b, while a number of groups (e.g. Mancini et al. 2013; Bean et al. 2013; Abe et al. 2013) have subsequently published secondary eclipses at or near the z-band consistent with ours, Lendl et al. (2013) found a significantly weaker z-band eclipse depth of 0.35$\pm$0.11 mmag.

Similar disagreements have been observed for WASP-12b: a hot Jupiter with a 1.1 d orbit around its G0-type host. Föhring et al. (2013) measured a z-band eclipse depth of 1.30$\pm$0.13 mmag, which was in stark contrast to the measurement of 0.82$\pm$0.15 mmag that López-Morales et al. (2010) had made previously. In the i-band, members of this group used WFC on the INT and IO:O on the LT to observe two secondary eclipses of WASP-12b separated by roughly a year (Hooton et al. in prep.). The measured depths of 1.01$\pm$0.18 and 0.52$\pm$0.24 mmag (see Figure 1) exhibit yet another example of this phenomenon. Observations of WASP-12b's transmission spectrum have shown similar disagreements: this time at the planet's terminator. Sing et al. (2013) found that WASP-12b was best fit with a featureless transmission spectrum. This was surprising, as the WASP-12b terminator is expected to be cloud-free, meaning pronounced spectral features should be visible. Kriedberg et al. (2015) performed a similar study and detected a water feature at 5σ. Without understanding the source of these disagreements, it is difficult to reliably constrain the temperatures, compositions and structures of the atmospheres of these exoplanets.

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, site locations and data analysis methods used to conduct these studies introduce large systematic errors to 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) have 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 Aristarchos telescope in Greece to observe five 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 five dates we apply for, we have already been successfully awarded time to carry out near-identical observations using the INT on La Palma. 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. Our strategy of observing with two telescopes thousands of kilometres apart will ensure that the effects of localised weather will not bias our conclusions. If we observe similar depths for individual eclipses with the two telescopes, our strategy of observing multiple WASP-12b eclipses across 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 shown to be due to systematics, conclusions based on previous observations at these wavelengths will be cast into doubt, and will inform future observational strategies to observe exoplanets at these wavelengths. If the disagreements are shown to be 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.

2 Facilities Requested

We request 5 nights of observing time using the LN CCD imager with the z-band filter on the Aristarchos Telescope to observe 5 secondary eclipses of WASP-12b.

To conduct this study, we need to observe the same secondary eclipses simultaneously with the two telescopes, and use the same methods of data reduction and analysis to measure the eclipse depths. Therefore, any observed disagreements between the eclipses depths measured by the two telescopes can be attributed to systematic errors associated with instrumentation and observing conditions. Our previous studies with the INT and LT demonstrate that 2 metre class telescopes are sufficient to conduct such a study (see Figure 1). The Aristarchos Telescope fulfils all these requirements, as well as being available in January, during which we have already been awarded time on the INT.

3 Observing Requirements

As secondary eclipses are time-critical events, we list the 5 nights for which this study is possible in section 5. The lunar separation is $>$60 degrees on all of these nights. These observations are not very sensitive to variations in seeing due to our strategy of defocusing the telescope. We are happy for these observations to be taken in service mode, or to attend in person.

We ask for 5 nights observation as this will help us effectively detect any time-dependent changes in the thermal emission properties of the WASP-12b dayside atmosphere that occur throughout the month. The full allocation of 5 nights would help us best monitor any variability in the atmosphere of WASP-12b. A minimum allocation of 3 nights would be useful for assessing the impact of different systematics between the two sites.

4 Observing Plan

We will follow a near-identical observing strategy to the observations that will be carried out simultaneously at the INT, which will be the same as the strategy that successfully detected the secondary eclipse in the i-band on the INT (see Figure 1). These observations require a very high precision in order to detect the small signal from the planet. We will significantly defocus the telescope to spread the light over many pixels, allowing for a longer integration time as well as reducing the impact from pixel-to-pixel sensitivity variations not taken out by flat-fielding.

To reduce overheads and achieve a high cadence, we set the exposure time to 60 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$1250. We will be able to obtain $\sim$100 frames during the eclipse, resulting in theoretical 5σ detection limits of $\sim$400ppm (0.4mmag). This is more than sufficient to detect and distinguish between eclipse depths of the size previously reported for WASP-12b (0.82$\pm$0.15 and 1.30$\pm$0.13 mmag from López-Morales et al. 2010 and Föhring et al.2013, respectively.

5 Scheduling Requirements

We request 5 nights of observation on the Aristarchos Telescopes—1 per eclipse. Below we list the nights on which a secondary eclipse of WASP-12b is visible from Aristarchos Telescope for which we have already been awarded time on the INT. Note that the dates are for the start of the night.

January 1, 11, 12, 23, 24.

6 References

Abe et al. 2013, A&A, 553, 49
Armstrong, De Mooij et al. 2016, Nat. Astron, 1, 4
Bean et al. 2013, ApJ, 771, 12
Burton, Watson, Gibson et al. 2012, ApJS, 201, 36
Föhring et al. 2013, MNRAS, 435, 2268
Fortney et al. 2008, ApJ, 678, 1419
Hebb et al. 2010, ApJ, 708, 224
Hubeny et al., 2003, ApJ, 594, 1011
Knutson et al. 2007, Nature, 447, 183
Kreidberg et al. 2015, ApJ, 814, 66
Lendl et al. 2013, A&A, 552, A2
López-Morales et al. 2010, ApJ, 716, L36
Madhusudhan 2012, ApJ, 758, 36
Mancini et al. 2013, MNRAS, 436, 2
Sing et al. 2013, MNRAS, 436, 2956

7 Figures

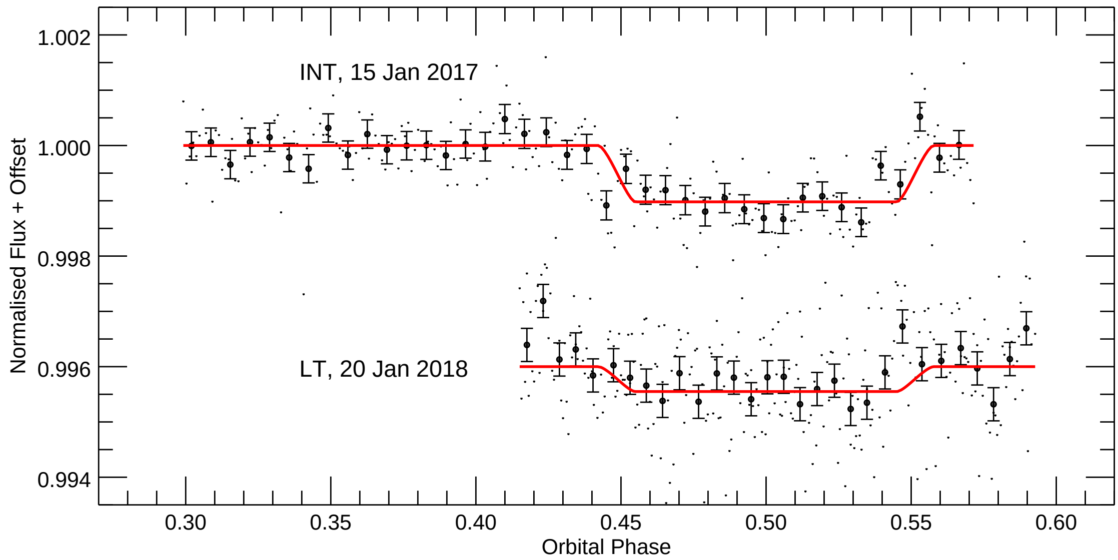

Figure 1: Light curves for i-band secondary eclipses of WASP-12b observed a year apart, taken from Hooton et al. (in prep.). The INT light curve (top) is best fit with an eclipse depth of 1.01±0.18 mmag. The LT light curve (bottom) is best fit with an eclipse depth of 0.52±0.24 mmag. This is just one example the stark contrast between measured eclipse depths in the red-optical. This also demonstrates the ability of 2 metre class telescopes such as Aristarchos to perform such a study, as well as this group's ability to observe, reduce and analyse high-precision photometry.

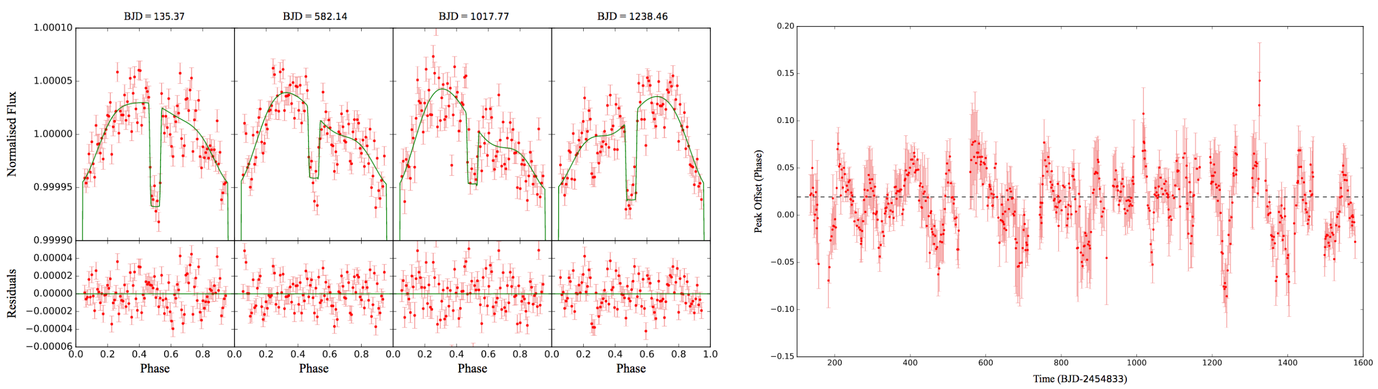

Figure 2: Left: Four selected full-phase curves from four years of Kepler photometry of HAT-P-7b, from Armstrong et al. (2016). In the left three panels, the peak flux occurs before the secondary eclipse; in the rightmost panel, the peak flux occurs after the secondary eclipse. Right: The variation in 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. This study will look for changes in the secondary eclipses of WASP-12b over the course of a month.

Students involved

Student	Level	Applicant	Supervisor	Applicant	Expected completion date	Data required
Matthew Hooton	Doctor	Yes	Dr Christopher Watson	Yes	2019/09	No
Ms Stephanie Merritt	Doctor	Yes	Neale Gibson	Yes	2019/09	No
Mr Jean Costes	Doctor	Yes	Dr Christopher Watson	Yes	2020/09	No
Mr Jamie Wilson	Doctor	Yes	Neale Gibson	Yes	2020/09	No

Linked proposal submitted to this TAC: No

Linked proposal submitted to other TACs: Yes

Proposal to observe secondary eclipses with the INT during January (ID I2018B/9), which has already been accepted and scheduled. For all the nights we ask for in this proposal, we have already been awarded time on the INT. The ability to observe the same WASP-12b secondary eclipses simultaneously with two instruments on telescopes in different locations will enable us to distinguish between whether previously observed disagreements in eclipse depths are due to variable weather on the planet, or due to systematic effects due to different telescopes, instruments and observing conditions.

Relevant previous Allocations: No

No additional remarks

Related Publications

Gibson et al. 2010, MNRAS, 404, L114: Ground-based detection of thermal emission from the exoplanet WASP-19b

Burton, Watson, Gibson et al. 2012, ApJS, 201, 36: z'-band ground-based detection of the Secondary eclipse of WASP-19b

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

Armstrong, De Mooij et al. 2016, Nat. Astron., 1, 0004: Variability in the atmosphere of HAT-P-7 b

Observing run info :

Run: A backup strategy: Due to our strategy of defocusing the telescope, these observations are fairly robust against poor seeing conditions.

Applicants

Name	Affiliation	Email	Country		Potential observer
Ms Stephanie Merritt	Queen's University Belfast	smerritt01@qub.ac.uk	United Kingdom		Yes
Mr Jean Costes	Queen?s University Belfast (Physics)	jcostes01@qub.ac.uk	United Kingdom		Yes
Mr Jamie Wilson	Queen's University Belfast (Astrophysics Research Centre)	jwilson34@qub.ac.uk	United Kingdom		Yes