Science and Technology Facilities Council | **PATT2**
Polaris House, North Star Avenue, Swindon, SN2 1SZ | **Version 02/2013**
Telephone 01793 442000 Fax 01793 442002

APPLICATION FOR TELESCOPE TIME (OPTICAL AND INFRARED)

1 TELESCOPE *(AAT, UKST, WHT, INT or UKIRT)*	INT	Reference: I/2018B/9	Date stamp: 17 Mar 2018
2 SEMESTER	2018B	3 SCIENTIFIC CATEGORY	1
4 COORDINATED PATT PROPOSALS	*AAT:*☐ *UKST:*☐ *WHT:*☐ *INT:*☐ *UKIRT:*☐ *JCMT:*☐ *GEMINI:*☐ *LT:*☐ *MERLIN:*☐		

5 PRINCIPAL APPLICANT

Surname: Hooton Title: Mr First name: Matthew
Post held: PhD Student
Address:
Astrophysics Research Centre
Queen's University Belfast
Belfast BT7 1NN
Telephone: +44 (0)28 9097 6365 Fax: +44 (0)28 9097 3110
E-mail: mhooton01@qub.ac.uk Is the applicant a possible observer? Yes

6 COLLABORATORS

Name:	Institute:	Observer?
Dr. Ernst de Mooij	Dublin City University	Yes
Dr. Chris Watson, Dr. Neale Gibson	Queen's University Belfast	Yes
Andrew Thompson, Stephanie Merritt	Queen's University Belfast	Yes
Jean Costes, Jamie Wilson	Queen's University Belfast	Yes

7 SHORT TITLE OF PROPOSAL *(maximum 12 words)*

PIES: The Photometric INT Exoplanet Survey. Targeted followup of the extremely hot-Jupiter WASP-12b

8 SUMMARY OF PROPOSED OBSERVATIONS

In our PIES survey to use the INT to categorise the atmospheres of hot-Jupiters, all but one night in our 2016B allocation was lost to weather. However, on the one clear night we obtained a $\sim 5\sigma$ detection of the secondary eclipse of the extremely hot-Jupiter WASP-12b in i'-band at 0.99$\pm$0.16mmag. This would constitute the first robust ground-based detection of planetary thermal emission in the i'-band and demonstrates the capability of the INT to perform such studies. We propose to observe secondary eclipses of WASP-12b in the i- and z-bands. This will allow us to confirm our previous detection, and resolve the large differences between previous observations in the z-band. As these bands probe the SED in the Wien limit, they put tight constraints on WASP-12b's energy budget. We will also measure its albedo in the U-band, probing the effects of hazes inferred from the planet's transmission spectrum. The detection of reflected starlight from another planet would likely attract significant press attention.

9 FOCAL STATION, INSTRUMENT AND DETECTOR

Focal station:	Instrument:	Detector(s):	Gratings/Filters:
prime	WFC	WFC	U, i', Z

10 OBSERVING TIME REQUESTED THIS SEMESTER

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Time requested this semester	3		6	n
Minimum useful allocation this semester	0		4	

UKIRT applicants requiring dark time must justify this in section 18

11 COMPLETE THIS SECTION ONLY IF THIS IS A LONG TERM PROPOSAL

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Total time requested				

Justification for long term status must be given in section 17

Text fonts must *not* be smaller than the style-file defaults

12 SCHEDULING INFORMATION

Preferred dates:	Time critical - dates listed below.
Impossible dates: *Give justification for impossible dates*	Our observations are strictly time critical and should only be scheduled on the nights listed in the "Any other scheduling constraints" box. No eclipses visible outside the indicated nights.
If observations are to be simultaneous with other telescopes or satellites, give details:	
Any other scheduling constraints: *Include likely clashes with other time applications, constraints on lunar position or quarter, instrument preparation requirements, etc*	Below we give list the nights on which a secondary eclipse of WASP-12b is visible from La Palma, and the moon is >30 degrees away. Note that the dates are for the start of the night. November 3, 15 & 27 ; December 8, 9, 19, 20 & 31 ; January 1, 11, 12, 13, 23, 24, & 25

13 SERVICE OBSERVING

yes: [ ] no: [x] maybe: [ ]

14 SUPPORT ASTRONOMER REQUESTED AT TELESCOPE

every night: [ ] no: [ ] first night only: [x]

15 LIST OF PRINCIPAL TARGETS

Object(s):	RA(h,m):	Dec(degs):	Mag(type):	Colour:	Exp. Time:
	(2000)	(2000)	V	V-K	(s)
WASP-12	06 30 32.794	+29 40 20.29	11.57	1.39	60

16 LIST ALL SIMILAR/SUPPORTING APPLICATIONS TO ANY PATT OR OTHER TIME ASSIGNMENT COMMITTEE

You must include a brief description of any other applications whose targets or science goals are similar to those requested here

Telescope/satellite:	Title/Description of programme:

17 SCIENTIFIC JUSTIFICATION

Case not to exceed this A4 page. Figures and/or references can be included on page 4a

PIES: The Photometric INT Exoplanet Survey – The aim of PIES is to demonstrate the capabilities of the INT for high-precision exoplanet observations as we enter the era of discovery missions such as NASA's Transiting Exoplanet Survey Satellite (TESS). So far, the PIES program has been allocated observing time in the 16A, 16B and 17A semesters.

In this proposal we request 9 nights of INT time to perform a detailed study of the extremely hot-Jupiter WASP-12b in the U-, i'- and Z-bands. The U-band observations will be aimed at measuring the planet's reflected light, while the i'- and Z-band observations will probe the planet's thermal emission blue-wards of its peak. This is based on the science case of I/2016B/P6 (PI De Mooij) which was awarded 9 nights. Unfortunately, only 1 out of 9 nights was clear – the rest were badly affected by cloud or lost completely due to weather, leaving us unable to complete our science goals.

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 ∼3000K. Crossfield et al. (2012) show that the planet's SED could be approximated with an isothermal model of ∼3000K. However, Föhring et al. (2013) find that the planet's emission spectrum could be better fit with a carbon-rich atmospheric model, which is also supported by Stevenson et al. (2014).

Interestingly, the z-band measurement from Föhring et al. (2013) is discrepant by 3σ compared to the measurement from Lopez-Morales et al. (2010) - see Fig. 1 - and also show disagreement with the best-fit model from Stevenson et al. (2014). This could be due to either systematic effects in the data, or weather on the planet. This shows the importance of repeat observations. We note that our i'-band measurement is also high compared to the models from Stevenson et al. (2014).

In addition to emission observations, WASP-12b's atmosphere has also been studied in transmission. Sing et al. (2013) show, using data from HST, that the transmission spectrum shows signs of aerosols scattering the light. If the haze has properties similar to the haze seen in HD189733b (e.g. Sing et al. 2011, Evans et al. 2013), this could imply a high albedo (∼0.4) at blue optical wavelengths.

Determining robust eclipse depths in the red optical – On the one clear night of our allocation during the 16B semester, we extracted a 0.99±0.16 secondary eclipse. To date, published detections of secondary eclipses of exoplanets in the i'-band are limited to Kepler results as part of a much wider optical bandpass (e.g. Armstrong, De Mooij et al. 2017) and a tenuous, 2σ detection from the ground (Abe et al. 2013). Although our detection has a large formal significance, we need to repeat the observation to confirm the measured depth, especially as it indicates a deeper than expected eclipse.

We propose to combine 3 observations in the i'-band with 3 observations in the Z-band, revisiting the tension between the eclipse measurements in the z-band from Lopez-Morales et al. (2010) and Föhring et al. (2013). By observing multiple eclipses in each band, we can directly determine the reliability of our measurements and mitigate the effects of systematics, thereby providing a robust measurement. These observations probe the planet's emission spectrum in the the Wien-limit, and are therefore very sensitive to the temperature of the emitting layer. *By combining the i'- and Z-band measurements, we will be able to put strong constraints on the planet's energy balance as well as its C/O ratio. This would also 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.*

Measuring the reflected light from an extremely hot-Jupiter – Due to its proximity to its host-star and its inflated radius, WASP-12b is an excellent target to search for reflected light. For an albedo of 1 (ruled out by thermal emission), the eclipse depth due to reflected light would be ∼1.5mmag! Bell et al. (2017) observed a single WASP-12b eclipse using HST/STIS from 290nm to 570nm, and placed an upper limit of 0.064 (97.5% confidence) on the geometric albedo across this range. As the albedo for hot-Jupiters is expected to drop off at wavelengths >400nm (Burrows et al. 2008), the albedo at shorter wavelengths can be significantly higher, e.g. their upper limit in the U-band is 0.45 (97.5% confidence). In addition, there is an interruption during every orbit of the HST, which can result in non-repeatable variations between orbits. Indeed, the negative eclipse depth measured in the HST white lightcurve could be caused by such an offset. In contrast, ground-based observations with the INT will be continuous, and likely have a higher duty cycle. We therefore propose to observe 3 eclipses in the U-band with the INT. *This would provide the first unambiguous ground-based detection of reflected light from an exoplanet, as well as the first direct albedo measurement of an extremely hot-Jupiter.*

18 TECHNICAL INFORMATION (I)

Give details of the technical feasibility of the proposal (S/N,etc) AND any non-standard technical requirements

Strategy – These observations require very high precision. In order to achieve this with the INT, 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. Since guiding with the autoguider is impossible in the case of short exposures, especially when significantly defocused, we will use a custom observing script that has been developed by Ernst de Mooij in collaboration with staff at the ING. This script uses the science images to measure any drift in each science frame and correct it. It also has the added benefit that it removes any drifts that might otherwise be caused by flexure when using an autoguider, while simultaneously automating the observations – making these observations very straightforward. In order to increase the cadence and reduce the overheads, we will use fast read-out.

Transit observations of the exoplanet HD189733b in the U-band obtained as part of a separate program *during bright time* in previous semesters strongly indicates that we can reach the precision necessary for this proposal (see Fig. 2). We note that, while these observations give us confidence in the feasibility of this study, they were unguided and not corrected for telescope drifts, and are therefore not optimal for this work. Using the guiding script that is now available, we will improve on this.

For WASP-12b in the U, i'- and Z-bands we will use an exposure time of 60 seconds, resulting in a cadence of 90 seconds. In the i'-band we expect to be limited by scintillation noise to a precision of ∼0.3mmag per frame, while in the U- and Z-band we will be limited by photon noise to ∼1.2mmag and ∼0.8mmag respectively per frame. The eclipse of WASP-12b lasts almost 3 hours; we therefore expect to obtain ∼120 frames per eclipse. Note that due to the significantly increased sky background in the U-band during bright time, we request dark time for the U-band observations in order to reach the high-precision required.

For a single eclipse, this results in a 5σ detection limit per eclipse of ∼0.55mmag, ∼0.18mmag and ∼0.37mmag in the U-, i'- and Z-band respectively. In the U-band this corresponds to a 5σ limit on the albedo of ∼0.37, approximately the albedo of HD189733b measured by Evans et al. (2013). This is a significant improvement on the upper limit of 0.45 (97.5% confidence) from Bell et al. (2017) in this wavelength range. In the i'- and Z-bands the resultant limit is more than sufficient to detect the thermal emission, which in the i'-band is expected at a level of ∼0.4-0.8mmag (although our 2016 observations indicate a ∼1 mmag depth), while in the Z-band the observations indicate a depth between 0.8mmag (Lopez-Morales et al. 2010) and 1.5mmag (Föhring et al. 2013).

We request to observe multiple eclipses in each band in order to build up the confidence in the reliability of any detected signal, and in the U-band to improve our detection limit, which, by combining 3 eclipses, allows a 5σ limit on the albedo of 0.2, and a 3σ limit of A=0.12, a factor of ∼4 better than the upper limit in this wavelength range from Bell et al. (2017).

We note that since we are measuring the secondary eclipse, stellar activity (e.g. starspots), will not impact these observations.

Target observability and scheduling constraints – In addition to the 3 hours of in-eclipse observations, we require >5 hours of out-of-eclipse baseline observations per night, against which the secondary eclipse depths will be measured. This baseline will also allow us to correct for systematic effects. We therefore require a full night per eclipse. As we wish to measure the eclipse three times in three different bands (i', Z and U), we request a total of 9 nights.

Although we believe the case for observation in the U-band to be compelling in its own right, it should be noted that if the panel considers this of lesser importance then we will accept an allocation without any nights set aside for U-band observation. Whilst we wish to stress the importance of taking repeat observations to confirm any detections and have accordingly requested 3 eclipses in each band, an allocation of 2 eclipses in each band would still be useful. On nights where the target is not visible for the entire night, we will identify other transiting/eclipsing exoplanets to observe for the time that the target is not visible.

Below we give the dates on which a secondary eclipse of WASP-12b is visible from La Palma, and the moon is >30 degrees away. Note that these dates are for the start of the night.
November 3, 15 & 27; December 8, 9, 19, 20 & 31; January 1, 11, 12, 13, 23, 24, & 25

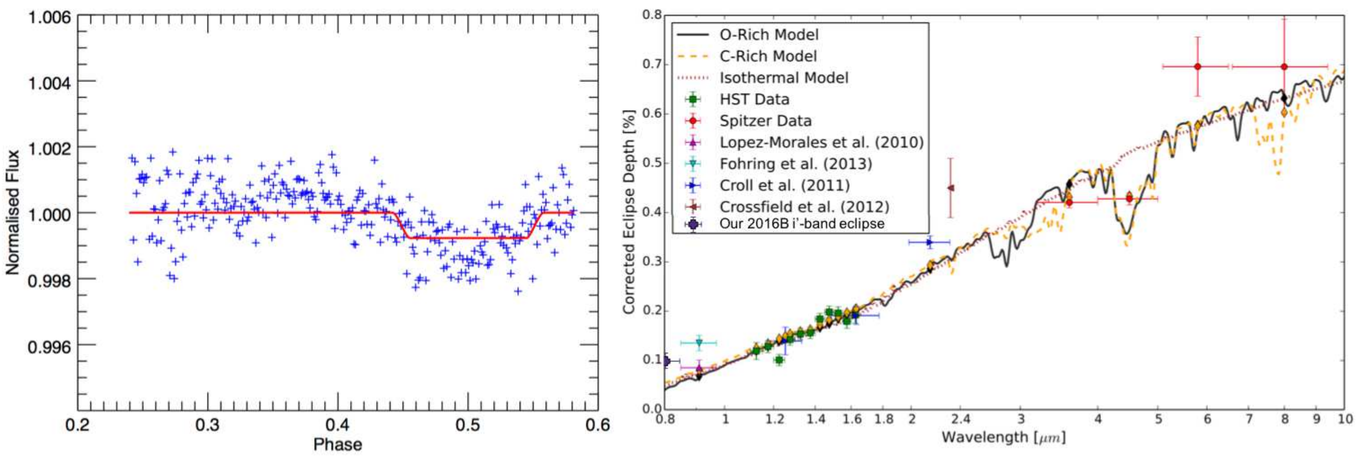

Figure 1: Left panel: i'-band secondary eclipse of WASP-12b taken with INT/WFC on the clear night of our 2016B allocation, fit using MCMC with an eclipse depth of 0.99±0.16 mmag at 5σ significance. Right panel: Emission spectrum for WASP-12b with three different atmospheric models overplotted, recreated from Stevenson et al. (2014). The discrepancy between the Z-band eclipse depth measurement of Lopez-Morales et al. (2010) and Föhring et al. (2013) is visible at 0.9 μm. Our i'-band eclipse measurement is the purple point on the far left of the diagram. Much like the Föhring et al. measurement in z-band, our i'-band measurement is too deep to be fit by Stevenson et al.'s best fit model. (N.B. The central wavelength of the SDSS i'-band filter used is below the range of wavelengths shown in the plot, and hence is shown at the edge for ease.)

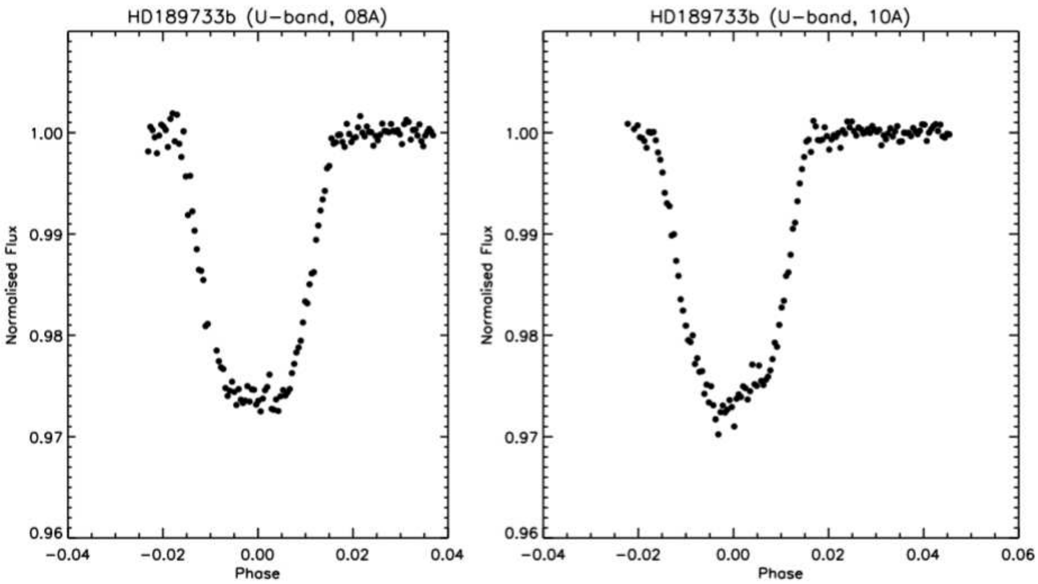

Figure 2: U-band transit observations of HD189733b obtained with the WFC on the INT in 2008 and 2010. These observations, which were obtained without any guiding or correction for telescope drift, demonstrate the capabilities of the INT for reaching the precision required for exoplanet studies. The bump in the second lightcurve at phase ~0.005 is due to a starspot.

REFERENCES

Abe et al. 2013, A&A 553, A49;
Bell et al. 2017, ApJL 847, 6;
Crossfield et al. 2013, ApJ 760, 140;
Föhring et al. 2013, MNRAS 435,2268;
Sing et al. 2011, MNRAS 416, 1443;
Stevenson et al. 2014, ApJ 791, 35;
Armstrong, De Mooij et al. 2017, Nat. Astron. 1, 0004;
Burrows et al. 2008, ApJ 682, 1277;
Evans et al. 2013, ApJL 772, 16;
Lopez-Morales et al. 2010, ApJL 716, 36;
Sing et al. 2013, MNRAS 436, 2956;

19 SUMMARY OF BACKUP PROGRAMME FOR POOR OBSERVING CONDITIONS

If instrumentation or setup differs from main programme, give full details

Our target is relatively bright, and the observations can proceed as long as the dome can be opened.

20 RELATED PATT APPLICATIONS OVER THE LAST FOUR SEMESTERS *(including unsuccesful applications)*

PATT reference:	Award:	Clear nights:	Comments:
I/2016B/P6	9 nights	1 night	Of the 9 allocated nights, only 1 night provided useful data.
I/2017A/P12	9 nights	9 nights	Reduction currently in progress.
W/2017A/P34	ToO		No observations triggered
W/2017B/P20	6 nights	3 nights	LIRIS broadband secondary eclipse observations of KELT-16b. Reduction currently in progress.
I/2017B/P13	4 nights	3 nights	WFC broadband secondary eclipse observations of KELT-16b. Reduction currently in progress.
W/2018A/P10	2 nights	-	Observations scheduled in June and July.

21 PUBLICATIONS BASED ON PATT TIME PUBLISHED DURING THE LAST FOUR SEMESTERS *(maximum 6)*

Barros et al., (2016), A&A, 593, 113, "WASP-113b and WASP-114b, two inflated hot Jupiters with contrasting densities" (LT+RISE)

22 EXPERIENCE OF INTENDED OBSERVERS WHO HAVE NOT PREVIOUSLY USED THIS TELESCOPE

All investigators on this proposal are highly experienced with high-precision photometry. De Mooij was part of the team that carried out the first ever ground-based detection of a secondary eclipse. Gibson led the team which detected the first K band secondary eclipse of WASP-19b (see Gibson et al. 2010). Watson was part of the team to detect the first z'-band secondary eclipse detection of WASP-19b (the 3rd ground-based z'-band detection in the world at the time - see Burton et al. 2012)

23 COMPLETE IF THE OBSERVATIONS ARE PRIMARILY FOR A STUDENT RESEARCH TRAINING PROGRAMME

Name of student:	Matthew Hooton
Project title:	Characterising exoplanet atmospheres

24 COMPLETE IF THE OBSERVATIONS ARE ASSOCIATED WITH A CURRENT STFC RESEARCH GRANT

Name of principal investigator:	
Grant title:	
Grant number:	

25 NON-STANDARD TRAVEL AND SUBSISTENCE REQUIREMENTS *(UK observers only)*

Justify requests for travel and subsistence for more than one person:

Details of any other expenditure (eg freight, remote observing):

PATT2 LaTeX style file v3.7 10 February 2008.