Science and Technology Facilities Council **PATT2**
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APPLICATION FOR TELESCOPE TIME (OPTICAL AND INFRARED)

1 TELESCOPE *(AAT, UKST, WHT, INT or UKIRT)*	WHT	Reference: W/2018A/10 Date stamp: Sep 16 2017	
2 SEMESTER	2018A	3 SCIENTIFIC CATEGORY	1
4 COORDINATED PATT PROPOSALS	*AAT:*☐ *UKST:*☐ *WHT:*☒ *INT:*☐ *UKIRT:*☐ *JCMT:*☐ *GEMINI:*☐ *LT:*☐ *MERLIN:*☐		

5 PRINCIPAL APPLICANT

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6 COLLABORATORS

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

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

Probing the thermal structure of the hottest-known exoplanet

8 SUMMARY OF PROPOSED OBSERVATIONS

The recently discovered hot Jupiter KELT-9b has a dayside temperature of ∼4,600 K, making it the hottest-known exoplanet and hotter than many K-type stars. The recent reported detection of a temperature inversion in the atmosphere of exoplanet WASP-121b adds weight to the theory that such inversions are caused by the presence of highly absorbing metal oxides in the atmospheres of the most irradiated planets. If true, KELT-9b is an outstanding target in which to observe a temperature inversion. We propose to use differential spectrophotometry to observe secondary eclipses of KELT-9b to build up its emission spectrum in the H- and K- bands. This will enable us to identify H_2O and CO features present at these wavelengths and use them to infer the presence of any inversion. This would be the first time an exoplanet's temperature inversion has been observed from the ground.

9 FOCAL STATION, INSTRUMENT AND DETECTOR

Focal station:	Instrument:	Detector(s):	Gratings/Filters:
Cassegrain	LIRIS	HgCdTe Hawaii	lr_hk

10 OBSERVING TIME REQUESTED THIS SEMESTER

	Dark:	Grey:	Bright:	specify nights *or* weeks:
Time requested this semester			3	N
Minimum useful allocation this semester			2	

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 of secondary eclipses given below.
Impossible dates: *Give justification for impossible dates*	All others not outlined in 'Any other scheduling constraints' below. No secondary eclipses visible.
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 KELT-9b is visible from La Palma. Note that the dates are for the start of the night. June 30; July 3 & 6

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)	K	V-K	(s)
KELT-9b	20 31 26.354	+39 56 19.77	7.482	0.07	30

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:

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 hot Jupiter WASP-121b ($T_{dayside}$ ~2700 K), on the basis of a detected water feature in emission (see Fig. 1) – the first detection of any spectral features in emission for an exoplanet. It 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 Hottest Known Planet – The discovery of KELT-9b, an ultra-short period, Jupiter-sized planet, was reported in June (Gaudi et al. 2017). Its host star has spectral type B9.5-A0 and $T_{eff} \approx$ 10,170 K, making it the hottest star known to host a transiting planet by ~2,500 K. KELT-9b's 1.5 day orbit around such a luminous host results in an equilibrium temperature ~1,000 K hotter than any known planet and as hot as late K-type stars. z'-band secondary eclipse observations of KELT-9b give a dayside temperature of 4,600 K - as hot as a mid-K star! The atmospheric structures and compositions of hot Jupiters with $T_{eq} \sim$ 1000-2500 K have been studied extensively, all of which thus far are cool enough to contain molecular species. However, the high temperatures present in the dayside of KELT-9b could support the presence of atomic metals in its atmosphere, known to be the main source of opacity in K-type stars. The ability to observe this planet presents the tantalising opportunity to study a planet in a qualitatively new regime of planetary atmospheres.

Objectives – We shall observe the secondary eclipse of KELT-9b in the H- and K-bands, which will allow us to obtain the shape of its SED. To do this, and to gain additional wavelength-dependent information, we propose to use differential spectrophotometry. This will allow us to spread the light over many spectral pixels rather than defocusing, avoiding the issue of diffraction spikes from the secondary impacting the target and reference star's PSF. This will also enable us to selectively bin the data in the spectral direction, enabling regions strongly affected by tellurics to be avoided, as well as the ability to select wavelength ranges containing interesting spectral features. Differential spectrophotometry is a very efficient technique for studies of exoplanet atmospheres, and results at optical and near-infrared wavelengths by Bean et al. (2010, 2011) and Gibson et al. (2013a,b - team member) have demonstrated its capabilities (Fig. 2).

In order to make sure our results are robust, we request at least 2 (preferably 3) secondary eclipse observations. Many results in the study of exoplanet atmospheres are based on single measurements in individual bands. However, independent repeat measurements of other objects (such as the z-band observations of WASP-12b – Lopez-Morales et al. 2010, Föhring et al. 2013), have shown significant discrepancies which affect the interpretation of the planet's spectrum.

KELT-9b is an excellent target for this study due to its brightness and the large expected secondary eclipse signals from which we will be building this emission spectrum. Making the assumption that K5 stars ($T_{eff} \approx$ 4600 K) are good proxies for the dayside of KELT-9b, we expect to see strong H_2O and CO features in the H- and K- bands (see Strategy section and Dhillon et al. 2000 Table 3 for more details). The precision afforded to us by WHT/LIRIS is more than sufficient to detect the these features and to identify whether they are present in absorption or emission. *If they are observed in emission, this would constitute the first time the temperature inversion of an exoplanet has been observed from the ground.*

18 TECHNICAL INFORMATION (I)

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

STRATEGY – At this stage, the composition of the atmosphere of planets in this temperature-regime is largely unknown. To the best of our knowledge, no model spectra have been produced for KELT-9b. Making the assumption that K5V stars are good proxies for these conditions, we have referred to relevant line lists to identify molecules likely to be present and identifiable in the KELT-9b emission spectrum (see Dhillon et al. 2000 Table 3 for an example). There is a strong CO feature present at 2.2935 μm and a wide H_2O feature present between 2.29 and 2.44 μm. There is also a strong Na feature at 2.20 μm and a strong Ca feature at 2.26 μm. The identification of these features, as well as whether or not they are visible in emission, is sufficient to discriminate between whether the layers that our observations probe are inverted or otherwise.

For these observations, we want to perform differential spectrophotometry of both KELT-9 and a nearby reference star of similar brightness using the spectroscopy mode of LIRIS. To get the best possible stability we shall use the 10" wide long-slit. The wide slit will prevent slit losses due to seeing variations and imperfect guiding, which would otherwise impact KELT-9 and the reference star differently. The reduction in spectral resolution due to the wide slit-width will not impact these observations, since the resolution for a point source is set by the seeing rather than the slit width and, in addition, we shall be wavelength binning the KELT-9 spectra in order to achieve a sufficiently high signal-to-noise ratio.

We note that our calculations are based on the most suitable reference star ($K_{mag} = 8.429$), 2.5 arcmin from the target. We will use an exposure time of 30 seconds that, when binning by 100 pixels (i.e. 10 wavelength bins across the H & K-band), will give us a SNR of 1500 per minute per spectral bin. In this calculation we have taken a very conservative estimate and assumed that the actual noise level will be twice the expected noise level (i.e. $\sigma_{measured}/\sigma_{expected} \sim 2$), as this is what we typically find for our broadband eclipse observations (e.g. De Mooij & Snellen, 2009; De Mooij et al. 2011). The eclipse lasts ~4 hours, and therefore the final expected 5-σ limit per spectral bin will be ~0.4 mmag. This detection limit is more than sufficient to detect the secondary eclipse in the case of a 4600K dayside, which is 2.4 mmag at 30-σ. Even if the layers probed in the near-infrared are cooler than those probed in the optical, we would still detect the 1.5 mmag eclipse depth for T=4,000K at $>15\sigma$ significance, and we can improve the SNR by rebinning the data into wider spectral bins.

Note that, at both optical and near-infrared wavelengths, Bean et al. (2010, 2011) and Gibson et al. (2013a,b) have demonstrated that differential spectrophotometry is capable of delivering the very high SNRs needed for transit and eclipse observations as outlined above (see Fig. 2).

We will perform the observations in staring mode with guiding, keeping the stars on the same position on the detector for the entire observations. Since this precludes direct subtraction of a background image, we will take a sequence of nodded observations at the start and end of the night in order to construct a background map.

We require out-of-eclipse baseline with respect to which the eclipse depth will be measured. This baseline will also allow us to investigate the red-noise on timescales of the eclipse duration and remove systematic trends with instrumental and atmospheric parameters such as airmass, seeing variations, and position of the star along the slit.

TIME REQUEST AND SCHEDULING REQUIREMENTS – Finally, we ask for time to observe at least 2 (preferably 3) secondary eclipses of this planet. This will not only help us to push towards smaller depths, but, more importantly, this will also allow us to build up the confidence in the reliability of any detected signal. We feel that it is important to obtain multiple observations of a secondary eclipse to ensure that any eclipse feature is not significantly impacted by systematics (which can sometime be of the same amplitude and duration of the features we are trying to detect).

The secondary eclipse of KELT-9b is a time-critical event and can only be observed on certain nights. Below we give the dates for the start of the night on which a secondary eclipse occurs:
June 30
July 3 & 6

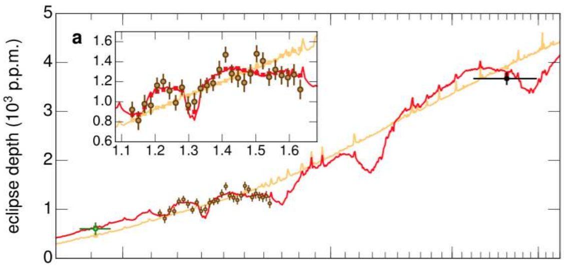

Figure 1: Emission spectrum for WASP-121b (Evans et al. 2017). The data points correspond to measured secondary eclipse depth with HST/WFC3 and the lines correspond to retrieval models for an inversion layer and an isothermal atmosphere (yellow). The presence of the marked water feature in emission is strong evidence for the presence of an inversion layer. Also tentatively marked is a potential VO feature, a molecule proposed to give rise to such inversions.

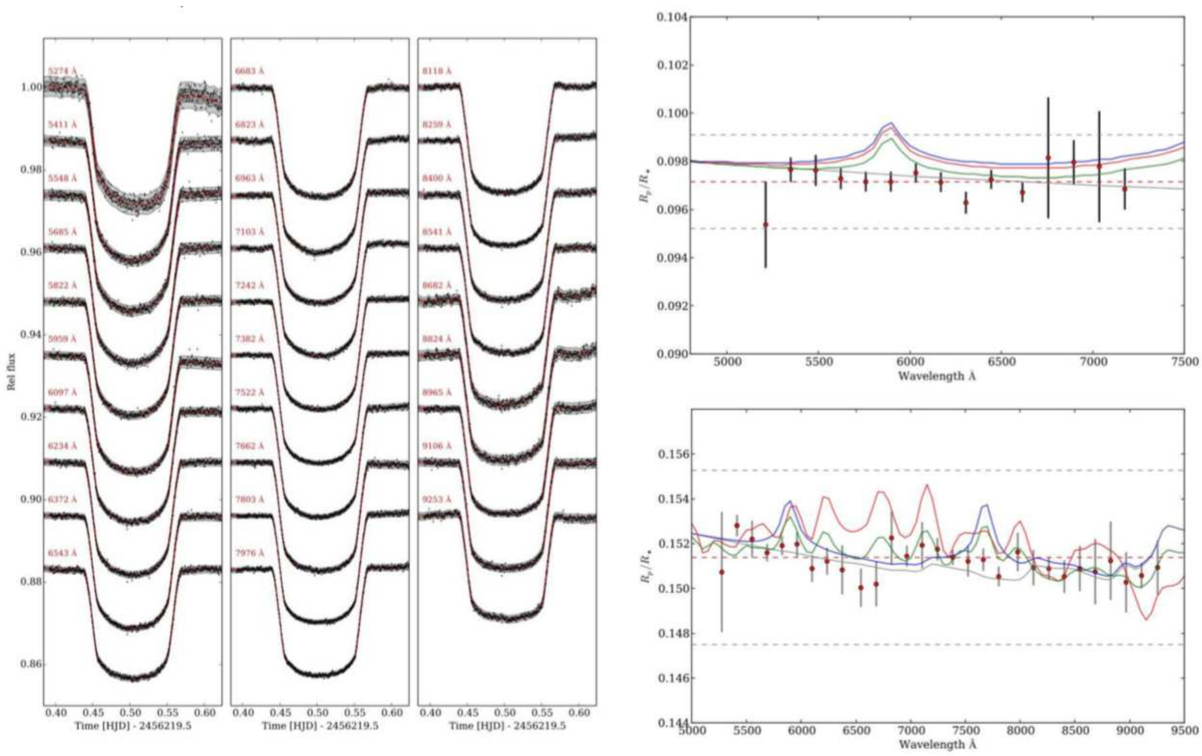

Figure 2: Left: spectral light curves of HAT-P-32b from a single transit observation using Gemini/GMOS (Gibson et al. 2013b). Right: Transmission spectra of WASP-29b and HAT-P-32b, reaching precisions of $\sim 10^{-4}$ (Gibson et al. 2013a,b). These observations demonstrate the power and feasibility of differential spectrophotometry.

REFERENCES

Bean et al., 2010, Nature, 468, 669
Bean et al., 2011, ApJ, 743, 92
Burrows et al., 2007, ApJL, 668, L171
De Mooij & Snellen, 2009, A&A, 493, L35
De Mooij et al., 2011, A&A, 574, 102
Dhillon et al. 2000, MNRAS, 314, 826
Diamond-Lowe et al., 2014, ApJ, 796, 66
Evans et al. 2017, Nature, 548, 58
Fortney et al., (2008), ApJ, 678, 1419
Gaudi et al., 2017, Nature, 645, 514
Gibson et al., 2013a, MNRAS, 428, 3680
Gibson et al., 2013b, MNRAS, 436, 2974
Harrington et al., 2007, Nature, 447, 691
Line et al., 2016 AJ, 152, 203

19 SUMMARY OF BACKUP PROGRAMME FOR POOR OBSERVING CONDITIONS

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

As our target and reference stars are bright, these observations are fairly robust against poor seeing conditions.

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.

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)

Burton, Watson et al., (2015), MNRAS, 446, 1071, "Defocused transmission spectroscopy: a potential detection of sodium in the atmosphere of WASP-12b" (WHT+ISIS)

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 is an expert in the use of differential spectrophotometry to study exoplanet atmospheres (Gibson et al. 2013a,b). 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 the atmospheres of extrasolar planets

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.