Thermal phase curves of hot Jupiters with IRSF

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Abstract

We will use IRSF/SIRIUS in an ambitious attempt to measure the thermal phase curve of a hot Jupiter exoplanet. The amplitude of the thermal phase curve will enable us to infer the efficiency of heat transport around the planet – a key parameter for understanding the atmospheres of these planets. If successful, this will be the first measurement of a thermal phase curve at K-band by any instrument. With the observations proposed we will also measure multiple secondary eclipses and transits. The eclipse depths will enable us to constrain the chemical composition and thermal structure of the planet's atmosphere. The timings of the secondary eclipses and transits will be used to look for dynamical evolution of the system due to the strong tidal forces or a third body in the system. The preferred target for this proposal is WASP-121 b, a bloated hot Jupiter (1.87 $R_{\rm Jup}$) that is close to the limit for tidal destruction. For an allocation of time in the second- half of the semester our target will be WASP-43 b, one of the shortest-period exoplanets known.

1 Scientific justification

The temperature on the day-side (irradiated hemisphere) of a hot Jupiter can be 3000 K or more, sufficiently hot for spectral features due to H_2O, CO, CH_4 and other molecular species to be detectable in the emission spectrum at infrared wavelengths. The makes it possible to estimate the composition of these planets' atmospheres, e.g., to infer the C/O ratio (Madhusudhan et al. 2011). The spectrum of the planet can be built up by measuring the depth of the secondary eclipse caused by the occultation of the planet at a range of wavelengths. There are many free parameters in the model atmospheres for hot Jupiters, often more than the number of observations available, so for most planets the constraints on the properties of the atmosphere are quite weak. The WASP survey has discovered more than 120 exoplanets to-date, many of which have short periods, bright host stars and large radii. This makes it possible to observe these planets using a wide variety of instruments and techniques and so to better constraint the models.

A key factor in determining the properties of an exoplanet's atmosphere is the efficiency of heat transport to the night side of the planet. This can, in principle, be measured from the thermal phase curve, i.e., the variation in the apparent infrared flux around the planet's orbit. The phase of maximum light in the thermal phase curve also gives information about the dynamical properties of the atmosphere and can be compared to the predictions of 3-d global circulation models (e.g., Showman et al., 2015). However, measuring the phase and amplitude of the thermal phase curve requires photometry at infrared wavelengths accurate to 100 ppm or better over the time scale of the planets orbit ($1-2$ days or more). To-date, only space-based instruments (HST, Spitzer) have demonstrated the necessary stability to make such measurements. This makes such measurements very expensive to carry out and so only about 8 planets have been succesfully observed in this way (Wong et al, 2015). In general, it is found that heat transport is weak in the most irradiated planets like WASP-121 b (i.e., large thermal phase curve amplitude) but there is great diversity in the properties of these exoplanets, even within this limited sample.

The preferred target for this proposal, and the one that gives the best chance of success for these difficult observations, is WASP-121 b. We discovered WASP-121 b using the WASP-South instrument at Sutherland. Its orbital period is $P_{\rm orb} = 1.275$ d and its mass is M=1.2 $M_{\rm Jup}$ (Delrez et al, 2015). The planet's orbit is only 15% larger than the tidal destruction limit for a planet of this mass and radius. The host star is bright (K=9.4) and its spectral type is F6 V, so no complications from stellar magnetic activity are expected. WASP light curves show no star-spot modulation above $\sim$ 1 mmag. The day-side temperature of WASP-121 b is ≈ 3000 K. Combined with its large planet radius (1.87 $R_{\rm Jup}$) this leads to a secondary eclipse depth of 600 ppm at z'-band, large enough to measured using

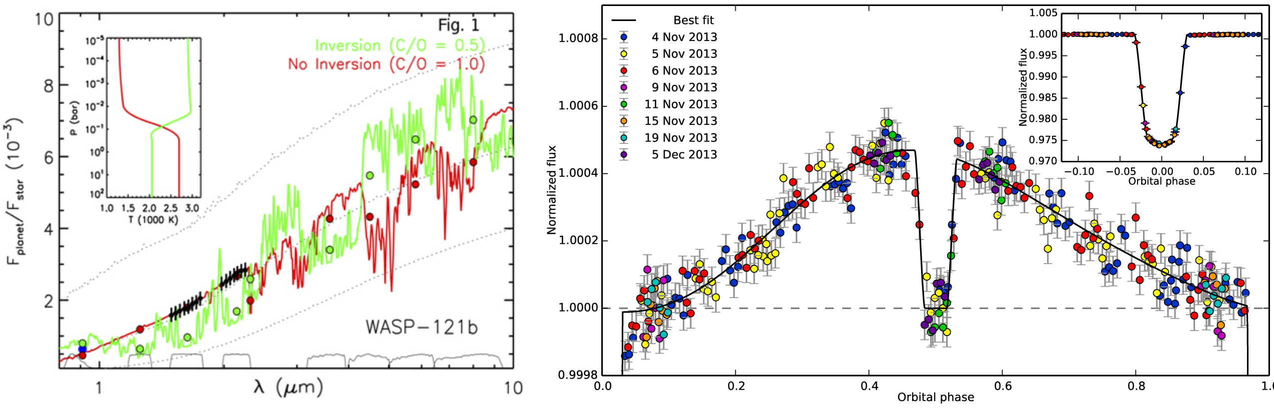

Figure 1: Left panel Model spectra for the WASP-121 planet-to-star flux ratio. The red and green lines depict atmospheres with different C/O ratios and with/without temperature inversions, as labelled The inset shows the corresponding pressure-temperature profiles. The dashed lines depict black-body atmospheres with temperatures of 2000, 2800, and 3800 K. Our TRAPPIST z'-band measurement is shown as a blue dot. The VLT/KMOS measurements expected for the model without inversion are in black. The circles are the band-integrated ratios of the models. **Right panel** Thermal phase curve of WASP-43 b from Stevenson et al. over $1.1-1.65\mu$m. The eclipse of the planet occurs at phase 0.5 and the transit (inset) occurs at phase 0. The sinusoidal variation in flux with its maximum near phase 0.5 and minimum depth similar to the secondary eclipse depth suggest that heat transport from the day side to the night side is inefficient, but observations nearer the peak in the spectral energy distribution (K-band) are needed to confirm this.

the 60-cm TRAPPIST telescope (Delrez et al, 2015). The secondary eclipse depth is expected to be $0.20-0.25$% at K-band (Figure 1). The peak-to-peak amplitude of the phase curve will be similar if, as expected, heat transport to the night side is inefficient. The dynamical history of WASP-121 b must have been interesting to place it at an orbital distance only 15% larger than its Roche limit and inclined almost perpendicular to the stars rotation axis (the sky-projected angle between the orbital and stellar rotation axes is $\psi \approx 260°$). This may point to dynamical interactions with a third body, e.g., another planet or a stellar companion.

WASP-121 b is a very low density ("bloated") hot Jupiter. The reason why some hot Jupiters are so large is not clear, but it does make it possible to study their atmospheres using transmission spectroscopy, i.e. the variations in the apparent radius of the planet as a function of wavelength due to opacity sources in the atmosphere near the day-night terminator. We will measure the apparent radius of WASP-121 b at J, H and K. The high precision of the light curves and well-defined transit depth at infrared wavelengths (due to the lack of limb-darkening) may make it possible to detect molecules in WASP-121 b's atmosphere from these observations alone. They will certainly provide a well-defined baseline against which to compare radius measurements at other wavelengths. Spectroscopy of the eclipses of WASP-121 b will also observed at H- and K-band using KMOS on VLT (ESO programme 096.C-0423). By comparing all these observations to models we will be able to infer the thermal and chemical properties of WASP-121's atmosphere (Fig. 1).

Another excellent target for this experiment in WASP-43, a hot-Jupiter that orbits a K7 V star with a period of less than 20 hours. Stevenson et al. have used more than 60 orbits of HST time to observe this thermal phase curve of WASP-43 b using low resolution spectroscopy over $1.1-1.65\mu$m (Fig. 1). They find that the amplitude of the phase curve at these wavelengths in almost equal to the depth of the secondary eclipse, i.e., the night side is very dark compared to the day side, which suggests that transport of heat to the night side of the planet is very inefficient. However, they were not able to find a model that can match the night-side spectrum of the planet so it is unclear whether this result over a narrow range of wavelengths below the peak in day-side spectral energy distribution can reliably be used to infer the energy budget. A thermal phase curve near the peak in the day-side emission spectrum at K-band will give a much less ambiguous picture of the energy budget in this planet's atmosphere. The expected amplitude of the thermal phase curve for WASP-43 b is expected to be similar to the measured K-band eclipse depth (0.18%; Zhou et al., 2015).

We will observe the selected target with IRSF/SIRIUS for 2 weeks using the observing mode succesfully developed to measure secondary eclipses of hot Jupiters (Fukui et al., 2014; Narita et al. ,2013a,b). We will measure the phase of secondary eclipse. This will put useful constraints on the planet's orbital eccentricity and repeated measurements of this phase together with monitoring of the transit times can be used to put useful constraints on the tidal and dynamical evolution of this planetary system.

IRSF/SIRIUS is one of only a few instruments in the world that has the field-of-view, proven instrument stability and time availability to succesfully measure the thermal phase curve of an exoplanet at K-band. We hope that these observations will establish a unique role for IRSF/SIRIUS in support of exoplanet observations with HST, Spitzer and, in a few years' time, JWST. Even if the measurement of the phase curve is not succesful, we will learn a lot about the planet using the high quality observations of the transits and eclipses that will be obtained.

2 Technical case

IRSF will allow us to access the Southern sky, where, due to the success of WASP-S (also located at SAAO, Sutherland), many of the known, bright, transiting planet systems are located. The IRSF/SIRIUS combination offers several advantages over other telescope/instrument combinations. Its wide field-of-view ($7.8' \times 7.8'$), allows multiple reference stars of comparable magnitude to the target star to be observed simultaneously. This is vital for de-trending the photometry of telluric atmospheric effects, in order to measure the small occultation signals accurately and precisely. Furthermore, SIRIUS offers the advantage of simultaneous photometry in three bands (J, H, K). This maximises the scientific return of a given occultation observation, as well as offering advantages when detrending the photometry.

IRSF/SIRIUS has been proven to offer high-precision photometry of stars of similar magnitude to our targets. Narita et al. (2013a,b) observed several transits of the GJ 1214 exoplanetary system, obtaining a precision of 100 – 200 ppm (parts per million) in their measurement of the transit depth. Fukui et al. (2016) made similar observations of the WASP-80 system (Fig. 3), obtaining similar levels of photometric precision, which are an order of magnitude less than a typical occultation depth. We will adopt a similar observing setup to those observations, employing position-locking software (without dithering) to keep the target within just 1 – 2 pixels of a fixed position throughout the observations. This, in combination with observations which are slightly defocussed is proven to minimise noise in the resulting light curves that may be caused by flat-fielding errors and/or pixel sensitivity variations.

Table 1: Hot Jupiter planetary system suitable for our experiment

Star	RA	Dec	K	P/d	Spec. Ty.	$R_{\rm pl}/R_{\rm Jup}$	Dates
WASP-121	07h 10m	-39°	9.4	1.275	F6 V	1.87	1 Jan – 15 Feb
WASP-43	10h 19m	-09°	9.3	0.813	K7 V	1.04	15 Feb – 1 Apr

3 Scheduling considerations

To measure the thermal phase curve it is essential to observe the target for 6–7 hours per night for about 2 weeks so that we resolve the sinusoidal signal on the planet's orbital period from the noise in the power spectrum that we expect on periods of about 1 day and on other time scale from variations in the Earth's atmosphere and small night-to-night variations in the instrument. The optimum time for observations of WASP-121 is the last 2 weeks of January 2016, but observations up to 2 weeks either side of this date are possible. The moon is near declination +16 at this time and the stars we are observing are bright, so the Moon will not have a large influence on the observations. During these two weeks we will be able to observe 3 complete transits and 2 complete secondary eclipses, plus some observations covering part of the secondary eclipse near twilight. WASP-43 can be observed during February and March for more than 6 hours per night.

4 Our team

PFLM has been involved in all aspects of the WASP project since it discovered its first exoplanets in 2007. He was P.I. of the Spitzer programme that succesfully measured the thermal phase curve of WASP-18 (Maxted et al., 2013) and was P.I. of the observing programme that measured the secondary eclipse depth of WASP-19 at H-band using VLT (Anderson et al., 2010). **BC** is a PhD student at Keele University and P.I. of ESO programme 096.C-0423 to obtain H+K-band spectroscopy of WASP-121 b. **SG** is a PhD student at Keele University and will analyse the observations obtained for his PhD thesis (superviser PFLM). **CH** is P.I. for the WASP-South instrument. **AMSS** and **DRA** are both post-docs with extensive experience of using infrared and optical telescopes such as VLT, Spitzer and the ESO 3.6-m telescope to characterise exoplanets. AMSS has previously used IRSF/SIRIUS to observe transiting exoplanets. **NM** has published over 50 peer-reviewed articles on the interpretation of exoplanets and their atmospheres using theoretical models. **EP** and **TM** bring their expertise in instrumentation development for exoplanet studies to this project. **AS** Has developed state-of-the-art global circulation models that have been used extensively to interpret observations of hot Jupiters with Spitzer and HST.

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