OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Aug–Dec **Proposal type:** short-term

Decoupling Stellar Variability from Extrasolar Planet Signals

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Abstract of Scientific Justification

Interpreting measurements of transiting exoplanets can be complicated by degeneracies between the transit depth and stellar variability. Here we explore a method of decoupling the stellar variability signal from the transit signal with an observing campaign on the hot-Jupiter WASP-33b using the 61”/Mont4k. WASP-33b offers the potential for high SNR measurements as it is the brightest (V=8.14) exoplanet with an equilibrium temperature above 2500K and has a large planet-to-star contrast ratio ($\sim$1.4%). It is the first planet known to orbit a δ-Scuti star, which are known to undergo pulsations that are driven by opacity variations. However, WASP-33b is not the only planet known to show variability in its transit measurement (e.g. HD189733b). The proposed observations are a follow up on our previous observations of WASP-33 which are needed to get a more precise characterization of the stellar pulsations. The goal is to understand and decorrelate the stellar variability from transit measurements using a Fourier filtering technique to better derive the depth of the lightcurve. We will target the shorter side of the optical spectrum using the Bessell-U filter, where the opacity is assumed to be dominated by Rayleigh scattering of molecular hydrogen. By targeting the wavelength region uncontaminated by atomic or strong molecular absorption features we assume the variability in the light curve is predominantly of stellar origin. Decoupling the stellar and planetary signals will enable detailed studies of the composition, cloud structure and temperature profile of an extraordinarily hot planet.

Summary of observing runs requested for this project

Run	Telescope	Cage	Instrument	PI	AO	Nights	Moon	Scheduling Optimal	Scheduling Acceptable	Sharing Poss.	Sharing Adv.
1	61”	f/13.5	Mont-4k			6	no pref	Nov–Dec	Oct–Dec	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: For extrasolar planets we need to observe on the nights that the planet is transiting their parent star. Additionally, the night before and after the transit are neccessary to characterize the stellar variability at an epoch closest to the transit. Table 1 in Scientific Justification lists all of the dates and times of the primary transits of our proposed target. We request a total of at least 6 nights such that we can obtain a full lightcurve and out of transit data for our object.

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A ⋆ appended to the proposal type indicates a continuation proposal; a ⋆ appended to the name of a proposer indicates the proposer is a (graduate) student; a proposer whose name is underlined is certified on the proposed telescope/instrument combination; if a ∗ appears within the PI or AO box in the observations summary table, the instrument is a PI instrument and/or Adaptive Optics are requested – signatures are required on the next page.

Target list (attach list if longer than 26 objects)

#	Object	RA	Dec	mag / color / type / redshift / comment / etc.
1	WASP-33b	02:26:51.05	+37:19:34.9	V=8.14,Transit Depth=0.0151mag

Approval for Instrument Use from PI: _____

*(have instrument PI signature appear on, or attach PI e-mail to, **all** copies)*

Graduate students *(provide the following information for **each** student named as PI or CoI on the cover page. Have the advisor's signature(s) appear on **all** submitted copies)*

Student's Name	Advisor's Name	Advisor's Signature	2nd-yr	Thesis
Kyle Pearson	David Koerner		no	yes

Scientific Justification

Background: WASP-33b is one of $\sim$1189 confirmed transiting planets. WASP-33b is a 'hot-Jupiter' with an orbital period of 1.22 days and a radius of 1.497 R_{jup} (Essen et al. 2013). WASP-33b is the only planet known to be orbiting a δ-Scuti star. δ-scuti stars are located in an instability strip covering spectral types between A and F on the Hertzsprung-Russel diagram. The host star exhibits low-amplitude p-mode oscillations at about 1 mmag semi-amplitude level (Cameron et al. 2010). Previous studies have only been able to place an upper limit on the mass of WASP-33b to $4.1M_{jup}$ due to extreme rotational broadening ($v\sin(i)\simeq 90\pm 10$ km s^{-1}) perturbing the RV measurements (Cameron et al. 2010). The A5 host star has an effective temperature of 7430 and with the planet being $\sim$0.025 AU away yields an equilibrium temperature for the planet of $\sim$2700 K given zero albedo and a uniform redistribution of incident flux. Thermal emission measurements in the K-band (Deming et al. 2012, Mooij et al. 2013, Smith et al. 2011) show the dayside temperature of the planet reaching as high as 3200K. The difference between the equilibrium temperature and day side temperature is uncommonly large for hot-jupiter planets but expected for exceptionally hot exoplanets because they radiate their heat on short timescales (Perez-Becker and Showman 2013).

WASP-33b provides us with the unique opportunity to study stellar variability on a short time scale compared to other variable systems e.g. XO-2b (Zellem et al. in Prep.) and HD-189733b (Pont et al. 2007). Previous campaigns have observed the host star of WASP-33b in order to characterize the variability (Essen et al. 2013, Smith et al. 2011). The most common pulsation signal of the star occurs around a frequency of $\sim$21 cycles per day which is consistent with our previous measurements as well. This pulsation oscillates a little more than 2 complete times throughout the whole transit and since it is on the order of $\sim$1mmag of the flux it easily stands out compared to the transit signal on the order of $\sim$15mmag (See Fig. 1). Based on the maximum pulsation strength of $\sim 0.1\%$ of the flux, that corresponds to a temperature change in the photosphere of the star on the order of $\sim$3K which facilitates the interpretation of transit measurements because the scale height of the planet's atmosphere will not vary drastically with time. This is important because the amplitude of spectral features in the planet's atmosphere is highly dependent on its scale height. Removing the stellar variability from extrasolar planet transits is crucial for interpreting transit measurements. The derived abundance's dependence on the radius is significant: a $\sim 1\%$ difference in the estimated planetary radius of 1000 K hot Jupiter at the 10 bar pressure level can result in variations in molecular abundances of 2 orders of magnitude or more (Griffith 2014). Here we propose to study the composition, temperature profile and clouds on the brightest hot-Jupiter. Chemical models of exoplanets (Moses et al. 2013) indicate such a hot atmosphere should be dominated by CO and H_2O, while brown dwarf observations suggest a dusty atmosphere of unknown particle composition.

Proposed Observations: We will observe the primary transit of the hot-Jupiter, WASP-33b, with additional monitoring of the star. Unlike typical exoplanet observations we require additional time to monitor the star a day before and a day after our transit event. In order to robustly remove the pulsations associated with stellar variability we need to have data unbiased by the transit signal and close in epoch to the transit event. It would be ideal to observe the star close in epoch to the transit event to ensure the chemistry in the star has not drastically changed and thus affected its variability. Also we are more likely to sample modes similar to the ones polluting the transit data. Once we are able to decouple the stellar pulsation signature from the data we will be able to study the pressure dependent radius of the planet and cloud structure which is necessary for establishing molecular abundances for exoplanets.

It has been suggested (Willems & Aerts 2002) that stellar pulsation modes may be induced by resonant tidal forcing by a close binary companion. Similar resonances have been studied for hot-Jupiter systems by looking at the spin-orbit coupling due to dissipative tidal forces (Ogilvie & Lin 2007). Due to the unusual retrograde orbit of WASP-33b little is known about whether it can excite pulsations in a star rotating the opposite direction. By monitoring the star before and after the transit we will gain insight on any phase induced stellar pulsations.

Table 1: Transiting Time Data (Listed in terms of priority)

Target	Date Requested	Ingress (Local Time)	Egress (Local Time)
WASP-33b	10-20	—	—
WASP-33b	10-21	22:45	1:37
WASP-33b	10-22	—	—
WASP-33b	11-11	—	—
WASP-33b	11-12	21:44	00:36
WASP-33b	11-13	—	—
WASP-33b	10-09	—	—
WASP-33b	10-10	23:16	02:08
WASP-33b	10-11	—	—
WASP-33b	10-31	—	—
WASP-33b	11-01	22:16	01:08
WASP-33b	11-02	—	—

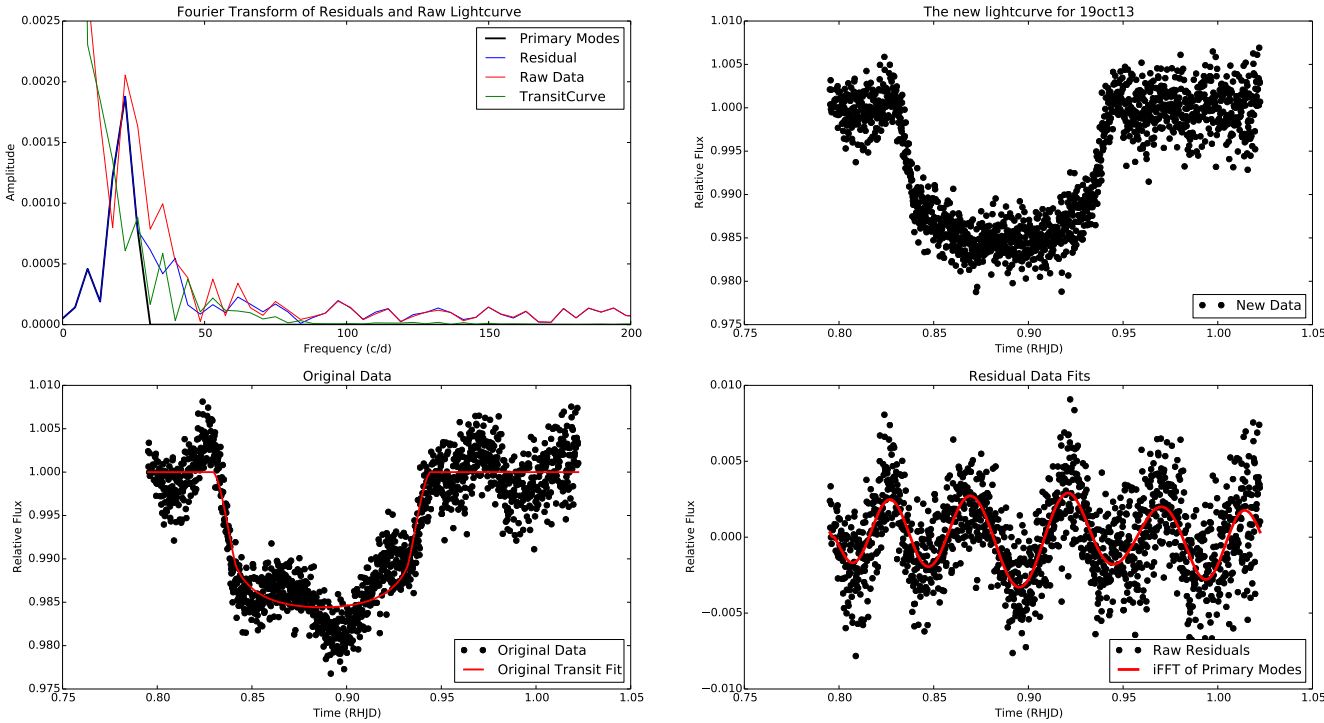

Fig. 1. Analysis dipicting the results from our Fourier filtering technique. Top left plot is the Fourier Transform of the raw data, residuals, and lightcurve model from our data set. The bottom left plot is the raw data with our best fit model transit. The bottom right plot shows the residuals from the data and model in the bottom left plot with the primary stellar modes shown in red. The top right plot shows the transit data after we remove the stellar variability using a Fourier filtering technique.

References

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Smith, A. M. S., Anderson, D. R., Skillen, I., Collier Cameron, A., & Smalley, B. 2011, MNRAS , 416, 2096
von Essen, C., Czesla, S., Wolter, U., et al. 2014, A&A , 561, AA48
Waldmann et al. 2011, arXiv:1104.0570
Willems, B., & Aerts, C. 2002, A&A , 384, 441
Zellem R., Griffith C., Pearson K., et al. in prep

Experimental Design & Technical Description *Describe your overall observational program. How will these observations contribute toward the accomplishment of the goals outlined in the science justification? If you've requested long-term status, justify why this is necessary for successful completion of the science.* ***(up to one page)***

Summary: We request at least 6 nights out of the 12 proposed for observing time to view the primary transit of the exoplanet WASP-33b using the Mont4K CCD on the 61" Kuiper telescope with the Bessell-U filter. The Mont4k CCD on the 61" Kuiper telescope has been shown to produce accurate photometry in transit-observation campaigns on other targets (Turner et al. (2013); Teske et al. (2013); Pearson et al. (2014)). Times of the primary transits of our targets are shown in Table 1. The table is arranged according to priority of dates, the ones nearest the top are our most preferred dates. In addition to the transit measurement we would like to observe just the star on the nights the planet is not transiting.

The target WASP-33b has a V-magnitude of 8.14. We intend to observe WASP-33b using the Bessell-U filter. From our previous measurements of this star we will use exposure times of $\sim$7 seconds. To optimize S/N levels and get faster readout times, we plan to use 3x3 binning of the CCD and read out only a portion of the CCD.

WASP-33b has a transit duration of $\sim$162 minutes which requires an observing cushion of 90 minutes before and after the transit to sample the stellar baseline. We will need atleast the same amount of time if not more on the nights we are just observing the star. Since WASP-33 exhibits short-term brightness variations, we request 3 consecutive nights of observations in order to characterize its brightness modes before, during, and after the planet transit takes place. We will use a Fourier-filtering technique to remove the stellar pulsations, which will allow our team to eliminate these systematic errors, and more accurately determine the planet's properties. By determining the modes of the star outside our transit event we hope to increase the robustness of our filtering technique when dealing with the transit data. See Figure 1 for results of one of our three previous data sets and the outcome using the Fourier-filtering technique based off elminating the main stellar pulsations from transit data.

To reduce the data, we will use the Exoplanet Data Reduction Pipeline, which utilizes the reduction method of Pearson et al. (2014), to eliminate sources of error that traditionally plague ground-based telescopes (e.g. Waldmann et al. (2011)). In addition, we will be using an in-house modeling routine based on a Markov Chain Monte Carlo (MCMC) technique (Ford 2005) to derive physical parameters of the planetary system. By removing the stellar variability component from our lightcurve we will increase the convergence rate and accuracy of our MCMC technique.

Kyle Pearson and Rob Zellem are certified on the 61" telescope with the Mont4k CCD.

Summary of Time Requested and Awarded *The TAC needs to understand the scope of this project — (1) tell us how many UAO nights you've already had for this project, how many you request this time, and (a good guess of) how many you need to complete the project; (2) if a substantial amount of observing for this project comes from non-UAO telescopes, tell us about that observing, and how the UAO part fits in; (3) if you are collaborating with people who have telescopes, especially if you are part of a large collaboration, tell us who is leading the project, and how UAO time and your participation fit in. (**up to one page**)*

This is a new project however we are using additional data that was collected under the EPO66 program. We have already recieved 3 nights of TBS time to observe WASP-33b which was obtained under the EPO66 program. To complete this project we should not need any extra time this semester unless we run into bad weather. The dates posted in Table 1 are in order of priority based on the altitude of the transit event.

Previous Use of Steward Facilities *List **all** allocations of telescope time for the present project and allocations for other projects on facilities available through UAO during the past 2 years, together with the current status of the data (cite publications where appropriate). Mark those allocations related to the present proposal (i.e, precede text with* `\related` *command). (**up to one page**)*

January 09, 14, 29, February 8, 11 2014:5 Nights were awarded on the Kuiper 61-inch telescope for observations of the hot-Jupiters, XO-2b and WASP-33b as well as the hot-Neptune, GJ-3470b. These observations are in preparation to be published, (Zellem et al in prep., Dragomir et al. in prep.).

September 21, October 18,19, November 1,2,9,15, 2013:7 nights were awarded on the Kuiper 61-inch telescope for observations of the hot-jupiter, WASP-33b and TrES-5b. These observations have been reduced and are being prepared to be published (Pearson et al. in prep.).

February 16, 26, March 18, 28, April 22, 2013: Five night's TBS time were awarded on the Kuiper 61-inch telescope for observations of the hot-neptune, GJ 3470b. These observations in conjunction with additional observations have been included in a publication constraining the planetary parameters of GJ 3470b (Biddle et al 2014). 2/16 was the only night not weathered out.