OBSERVING REQUEST
University of Arizona Observatories

Year: 2015 **Term:** Jan–Jun **Proposal type:** short-term⋆

Determining the Optical Transmission Spectra Slopes and Radii of Bright Exoplanets with the 61"/Mont4k and VATT/VATTSpec

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Abstract of Scientific Justification

Observations of transiting exoplanets yield their atmospheric temperature-pressure profiles, compositions, and even the presence of clouds/hazes and atmosphere circulation. However, interpreting measurements of transiting exoplanets is complicated by model degeneracies between the atmospheric pressure level and atmospheric composition; a $\sim$1% difference in the estimated planetary radius at the $\sim$1 bar pressure level can result in variations in molecular abundances of an order of magnitude or more. Here we request exoplanet atmosphere observations *outside* of the strong molecular and atomic absorption spectral regions, at optical wavelengths where the opacity is dominated by Rayleigh scattering and (if present) clouds/haze. We propose a concentrated observing campaign on 7 bright transiting exoplanets and a super Earth with the 61"/Mont4K in two optical filters (U and B). These targets have near-IR data, but lack measurements that are uncontaminated by strong molecular and/or atomic gas absorption features. Our 61" observations of XO-2b will be in support of a larger study to highly constrain this planet's H_2O abundance with upcoming *Hubble*/WFC3 and Gemini data. We will also confirm VATTSpec's capability for optical exoplanet spectroscopy by observing the primary transits of HD 189733b and WASP-33b, both of which offer the potential for high SNR as they are two of the brightest exoplanets with large planet-to-star contrast ratios. We aim to disentangle the physical radius and the atmospheric composition of these exoplanets, as well as monitor these targets for the presence and potential variability of clouds. Our observations, coupled with radiative transfer modeling, will determine an upper limit to the radius of each planet at a specified pressure level by breaking the degeneracy between the assumed/derived radius and composition.

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	Mont4k				no pref.	Jan–Jul	Jan–Jul	no	no
2	VATT	f/1	VATTSpec				no pref.	Jan–Jul	Jan–Jul	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: Please see "Time Requested" for details. We must observe during times that our exoplanet targets transit in front of their host stars. This restricts our requested time to specific nights and hours during those nights.

no text past this line

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	HAT-P-1b	22:57:46.844	+38:40:30.33	V=9.87
2	HAT-P-2b	16:20:36.358	+41:02:53.11	V=8.69
3	HAT-P-33b	07:32:44.218	+33:50:06.12	V=11.03
4	HD 189733b	20:00:43.713	+22:42:39.065	V=7.648
5	Kepler-138c	19:21:31.57	+43:17:34.7	V=13.5
6	WASP-33b	02:26:51.0582	+37:33:01.73	V=8.14
7	WASP-54b	13:41:49.028	−00:07:41.01	V=10.41
8	XO-1b	16:02:11.840	+28:10:10.43	V=11.25
9	XO-2b	07:48:07.0	+50:13:33	V=11.18

Approval for Instrument Use from PI: N/A

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
Robert Zellem	Caitlin Griffith		no	yes

Scientific Justification

Investigations of the atmospheric composition of transiting exoplanets have detected the main C and O-bearing species (H_2O, CO, CO_2 and CH_4) for a few of the brightest systems (e.g., Tinetti et al. 2007; Burrows et al. 2007; Knutson et al. 2007; Swain et al. 2008). During primary transit, when a planet passes in front of its host star, the light that transmits through its atmosphere reveals planetary absorption features. Transit observations include a fixed component of the solid disk of the planet and a wavelength-dependent component that is absorbed or scattered by the atmosphere. Such observations probe the $\sim$1 bar–1 millibar altitude region of the exoplanet's day-night terminator and scale with height. These measurements are directly sensitive to the column depth (at the exoplanet's limb) of individual molecular and atomic species and only weakly dependent on temperature (for a given scale height).

The most limiting aspect in the analysis of exoplanet transmission observations is the degeneracies in the radius as a function of atmospheric pressure and composition (Benneke & Seager 2012, 2013; Griffith et al. 2014). The derived pressure level at which the transit radii observations originates depends on the assumed abundance of molecular and atomic species in the atmosphere. Molecular abundances derived from primary transit spectra are constrained only to within $\sim$3–5 orders of magnitude (e.g., Madhusudhan & Seager 2009). The derived abundances dependence on the radius is significant: a $\sim$1% difference in the estimated planetary radius of 1000 K hot Jupiter at the $\sim$10 bar pressure level can result in variations in molecular abundances of 2 orders of magnitude or more (Griffith 2014). Essentially the solution set is degenerate; model atmospheres can have either a large radius and low gas mixing ratio or vise versa and block the host stars light equally well.

This degeneracy can be further complicated by the existence of clouds. Recent studies at visible wavelengths have found that some exoplanets have clouds (e.g., Demory et al. 2013, Kreidberg et al. 2014, Knutson et al. 2014), while others have relatively clear atmospheres (e.g., Fraine et al. 2014). However, it is unclear why some planets have clouds while others do not. Clouds can potentially indicate the planet's rotation rate for relatively fixed and broad-coverage clouds (Seager 2010) and influence the interpretation of both photometric and spectroscopic data.

We propose a concentrated, investigative study of the optical spectral characteristics of 8 exoplanets at wavelengths (0.35–0.55μm) that lie outside the strongest molecular gas absorption signatures. Here the atmospheric opacity is dominated by H_2 Rayleigh scattering and, if present, clouds. Thus we can disentangle the degeneracy between the physical radius and the atmospheric composition of the exoplanets by probing these "clear" spectral regions in which we can confidently assume absorption due to H_2 alone. In this way we are able to constrain the radius of the hot Jupiter XO-2b to 56σ using 61"/Mont4k U and B-band photometric data (Fig. 1 *Left*; Griffith 2014; Griffith et al. 2014). In addition, we will be able to conduct a dedicated study to detect (via the slope of our visible data, which will deviate from a H_2 Rayleigh scattering slope) and monitor possible cloud coverage in transiting exoplanet atmospheres.

This proposal concentrates on 8 of the brightest ($V >$11.25) exoplanets, offering the ability to conduct high precision measurements. Some of them have large radii, and therefore high contrast, while others have a large scale height, and therefore a large transit signal. They already have a substantial amount data longward of $\sim$0.60 μm (at least 5 photometric points), to which we can anchor our bluer data. We will measure the primary transit depths of these exoplanets in the B ($\sim$0.34–0.54 μm) and U ($\sim$0.305–0.425 μm) bands, which are free of any molecular or atomic absorption features. We will also obtain the first-ever U and B observations of Kepler-138c, a recently-discovered super Earth (Kipping et al. 2014). Based on our precision of previous XO-2b observations (Fig. 1 *Left*; Griffith et al. 2014), we predict that we can detect its primary transit depth to 3σ. We will also further test VATTSpec's capability for making optical spectral measurements by confirming our 2014A data of HD 189733b, which offers the potential for high SNR due to it being one the brightest exoplanets (V=7.63) with one of the largest planet-to-star contrast ratios (1.55%; Knutson et al. 2012). We ask here for at least 2 nights per target to confirm our measurements and in case of weather.

For our 61"/Mont4k targets (Table 1), our observations will be the bluest observations to date of their transmission spectra, and the only observations outside of strong molecular or atomic absorption bands.

The data will be reduced and analyzed to determine first whether the slope of optical absorption in the atmospheres of exoplanets generally mimics that of Rayleigh scattering (see Fig. 2). Such a finding, coupled with a lack of temporal variability, would suggest atmospheres devoid of clouds. This outcome would also allow us to derive an upper limit on the radius of the planet, as the opacity would be due to Rayleigh scattering of H_2 only, and the existence of clouds would imply a smaller radius. We will model the optical and published near-IR observations to constrain H_2O and potentially CO in the exoplanetary atmospheres given our constraints for the radius.

In particular, our 61" observations of XO-2b are in support of a larger program that aims to determine the C and O abundances to within a factor of 3 with coordinated, upcoming Gemini/GMOS and Hubble/WFC3 observations (PI: C. A. Griffith). With the 61", we will measure where XO-2b's atmospheric opacity is dominated by Rayleigh scattering and, if present, clouds (Fig. 2). Thus we can disentangle the degeneracy between the physical radius and the atmospheric composition of the exoplanet by probing these clear spectral regions in which we can confidently assume absorption due to H_2 alone. However high-precision observations at blue wavelengths are difficult because of high telluric extinction and telescope systematics. Here we propose to treat the resulting errors with simultaneous observations of XO-2b with Mayall/KOSMOS, the Discovery Channel Telescope (DCT) in northern Arizona and the 61" telescope. Since the transit depth will be a common signal shared between these telescopes, we will run a joint analysis of all datasets (see Experimental Design) to remove the non-common signals, i.e., red noise sources, and get closer to the photon noise limit. This analysis will also allow us to characterize the systematics of each platform so they can be removed in future studies. We will perform a similar systematic analysis with simultaneous observations of WASP-54b with the 61" and Harvard's FLWO 1.5 m (60") telescope to better quantify the systematics of each platform, permitting higher precision for these and future observations.

This project also includes participation from UofA astronomy and physics undergraduate members of the Arizona Ground-based Observing of Exoplanets group (AzGOE). This group uses UofA telescopes to characterize the thermal structure and molecular composition of transiting exoplanets while stressing undergraduate involvement at all parts of the analysis. PI Robert Zellem is teaching an independent study session where students learn how to observe transiting exoplanets and then reduce the data. The younger students will be involved in preparing and conducting observations and performing data reduction and analysis, whereas the older students will be involved in preparing observation proposals, learning the syntax for formal scientific publications, and the application of our results to the study of exoplanet atmospheres. Since extrasolar planets are at the forefront of observational astronomy, AzGOE provides the opportunity for participating members to be on high impact papers as well as gain valuable experience in this field of research.

References

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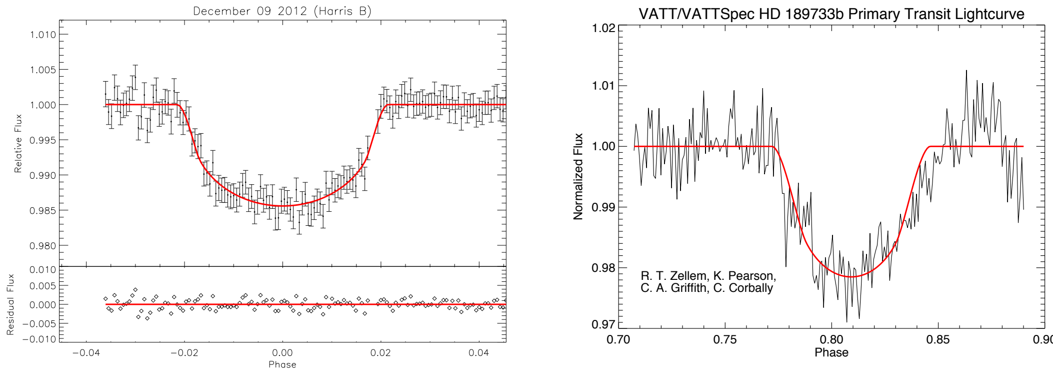

Figure 1: *Left:* A sample B-filter lightcurve of XO-2b which demonstrates the quality we are capable of achieving with the 61"/Mont4k. Its associated best-fit model is over plotted in red and the corresponding residuals are in the bottom frame. From such a lightcurve, we can make a 53σ detection of XO-2b's primary transit ($R^2_{planet}/R^2_{star} = 0.0106 \pm 0.0002$). (Griffith et al., 2014) *Right:* The first ever transiting exoplanet observation by VATT/VATTSpec. Here, our team makes a $\sim 10\sigma$ measurement of the hot Jupiter HD 189733b's primary transit in one of VATTSpec's 2600 spectroscopic channels, suggesting that VATTSpec is capable of high-precision transiting exoplanet spectroscopy. We request additional VATTSpec time this semester to confirm this observation and also record the visible spectrum of the hot Jupiter WASP-33b.

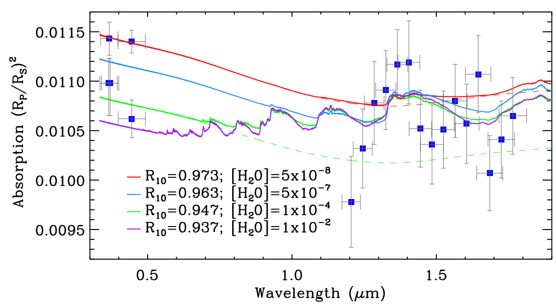

Figure 2: A plot of our 61"/Mont4k U and B-band photometry (points shortward of 0.6 μm) and previous $Hubble$/NICMOS measurements for XO-2b (all other data; Crouzet et al. 2013) compared to radiative transfer atmospheric models that include Rayleigh scattering, pressure-induced H_2 absorption with different 10 bar optically-thick planetary radii (R_{10}) and water abundances ($[H_2O]$). Our current retrieval of XO-2b's radius is largely limited by the scatter in our B-band photometry. We propose to observe XO-2b with additional nights on the 61"/Mont4k here not only to better constrain its radius via reproducibility but also to determine if its varying B-band radius is due to stellar variability or platform-specific systematics. (Griffith et al. 2014)

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)***

We request 12 nights to observe the primary transits of 7 different exoplanets (see Table 1) using the 61"/Mont4K and 4 nights to observe the primary transits of HD 209458b and WASP-33b with VATTSpec. The Mont4k CCD on the 61" telescope has been shown to produce accurate photometry in transit-observation campaigns on other targets (Dittmann et al. 2009; Dittmann et al. 2010; Turner et al. 2013; Teske et al. 2013; Griffith 2014; Griffith et al. 2014). This campaign is a continuation of TBS-proposals from 2012B and 2013A, UAO-S64 from 2013A, UAO-S58 from 2013B, and UAO-S60 from 2014A.

Obtaining photometry or spectroscopy across $\sim$0.3–0.5 μm is necessary to constrain the slope of the optical transmission spectrum of these bright exoplanets and fulfill our scientific objective. To determine to 1σ-confidence if the short-wavelength ($<$0.50 μm) slope is Rayleigh scattering (Fig. 2), we need an error on our transit-depth measurement of $\sim$1% or less. Previously with 61"/Mont4k (Fig. 1), we obtained errors of $\sim$1% in U-band with one night of good observing (Griffith 2014; Griffith et al. 2014). However, while we only need on one good observation to obtain the required precision for this project, we are requesting at least two per target to confirm our observations and in case of host star variability or weather. Any residual systematics will be treated with an array of procedures that we have successfully used to extract the planetary signal, such as the Self-Coherence Method, Independent Component Analysis (ICA), and Principal Component Analysis (PCA) (e.g., Swain et al. 2010, Thatte et al. 2010, Waldmann et al. 2012, Waldmann et al. 2013, Zellem et al. 2014). Our 61" data on XO-2b will also be compared with those measured by the DCT and Mayall and analyzed with an ICA and PCA to determine whether features detected in the lightcurve is red noise specific to the observing platform intrinsic to the planetary system. We will perform a similar systematic analysis with simultaneous observations of WASP-54b with the 61" and Harvard's FLWO 1.5 m (60") telescope to better quantify the systematics of each platform, permitting higher precision for these and future observations. In this way, we will quantify the effect of systematics specific to each observing platform, which will help future studies remove their effects and achieve higher SNR.

We need to observe full transits, as well as a pre- and post-transit baseline, using both filters. To optimize SNR levels and get faster readout times, we can use 3x3 binning of the CCD if necessary for the fainter target in our sample. We will be using the Exoplanet Data Reduction Pipeline to reduce our data (Turner et al. 2013; Teske et al. 2013; Griffith et al. 2014) and an already-developed in-house modeling package to obtain the planetary parameters. For the VATTSpec data, we will use the Zellem et al. (2014) reduction, which removes common-mode wavelength- and time-correlated errors sources with a PCA and then amplifies the transit signal over the noise by binning in Fourier-space. We have used this reduction to recover the H- and K-band emission spectrum of HD 209458b from a very noisy Palomar/TripleSpec ground-based dataset. We will also use our own hybrid version of the Swain et al. (2010) and Waldmann et al. (2012) reductions, which use a normalization to remove common-mode wavelength- and time-correlated errors and then amplify the transit signal by binning in Fourier space. These reductions have been used to repeatedly recover HD 189733b's near-IR emission spectrum observed with IRTF/SpeX on Mauna Kea.

A large portion of the 61" photometry data reduction will be conducted by Steward Observatory undergraduate members of the Arizona Ground-based Observing of Exoplanets group (AzGOE), under direction of PI Robert Zellem and Co-I Kyle Pearson. Robert Zellem will spearhead the VATTSpec reduction. The radiative transfer analysis and the implications for the planet's physical characteristics will be conducted by Robert Zellem and Co-I Caitlin Griffith. This entire project is part of Robert Zellem's PhD thesis.

These are time-sensitive observations, as there are very limited data in the transmission spectrum of our targets $\lesssim$0.50 μm. Our observations will be the bluest of these targets to date. We will publish this data detailing our results and placing them in context with the existing optical and NIR observations. We will constrain the exoplanets' radii, which is essential to enable accurate and informative modeling of their atmospheric compositions. Previous 61" photometric data of XO-2b (Fig. 1 *Left*) has allowed us to successfully constrain its radius and, when coupled with radiative transfer modeling of this data and simultaneously other published observations, its molecular composition (Griffith 2014; Griffith et al., 2014).

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**)*

We were awarded 4 TBS nights on the Kuiper 61" UAO telescope in 2012B and 3 nights in 2013A for this project on XO-2b. The results from these observations are to be published this fall. We were awarded 10 TBS nights during the summer of 2013A, however due to monsoons, all but 1 of the nights were lost. We were rewarded with 8 nights for semester 2013B, 3 of which were lost due to weather. We were awarded 11 nights last semester (2014A), all but 1 were lost due to weather. We are currently reducing these data. We were awarded 6 nights this semester (2014B).

The following table lists observing opportunities for our selected bright exoplanet targets at the VATT and 61" for 2015A.

Note: We are requesting at least up to 2 nights per target. In the table below, we list each night in order of preference, with the top 2 nights notated in bold. However, our observations of XO-2b are part of a larger collaboration, including *Hubble*/WFC3, Gemini, Mayall 4 m, and Discovery Channel Telescope time, we are requesting 4 nights here in support of this large-scale study.

Table 1: **Requested Primary Transit Dates & Times**

Target	**Date Requested** local start night	**Ingress** local time	**Egress** local time	**Platform**
HAT-P-1b	29-June	00:33	03:20	61"/Mont4k
HAT-P-2b	21-May	21:57	02:14	61"/Mont4k
HAT-P-33b	12-Jan	21:37	02:02	61"/Mont4k
HAT-P-33b	19-Jan	20:23	00:48	61"/Mont4k
HD 189733b	02-June	01:36	03:25	VATT/VATTSpec
HD 189733b	22-June	00:49	02:38	VATT/VATTSpec
Kepler-138c	17-May	21:49	00:53	61"/Mont4k
WASP-33b	16-Jan	19:53	22:35	VATT/VATTSpec
WASP-33b	27-Jan	19:23	22:04	VATT/VATTSpec
WASP-54b	15-Apr	21:26	01:55	61"/Mont4k
XO-1b	12-June	23:00	01:56	61"/Mont4k
XO-1b	02-Apr	00:16	03:12	61"/Mont4k
XO-1b	08-June	00:24	03:21	61"/Mont4k
XO-1b	29-Mar	01:40	04:36	61"/Mont4k
XO-2b	17-Jan	00:26	03:07	61"/Mont4k
XO-2b	25-Jan	20:52	23:27	61"/Mont4k
XO-2b	07-Feb	22:26	01:21	61"/Mont4k
XO-2b	28-Feb	20:55	23:36	61"/Mont4k
XO-2b	03-Apr	21:03	23:44	61"/Mont4k

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)***

⋆ Awarded 4 TBS nights in 2012B and 3 nights in 2013A (UAO-S64) for observations of XO-2b using the Kuiper 61". These observations have been published (Griffith 2014), submitted (Griffith et al., 2014), and in preparation.

⋆ Awarded 10 TBS nights in 2013B for observations for the exoplanet study on the 61"/Mont4k. All but 1 night were lost to monsoons. Currently reducing data.

⋆ Awarded 8 nights on the 61"/Mont4k to continue this exoplanet study in 2013B (UAO-S58). 3 nights were lost due to weather. Currently reducing data.

⋆ Awarded 11 nights on the 61"/Mont4k this semester (2014A), all but 1 were lost due to weather. Also awarded 2 nights on VATT/VATTSpec (1 for training + 1 for observing). Currently reducing data.

⋆ We were awarded 4 nights this semester (2014B) on the 61"/Mont4k and 2 nights on VATT/VATTSpec. Currently observing.