OBSERVING REQUEST
University of Arizona Observatories

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

The Ionosphere of an Exoplanet

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Abstract of Scientific Justification

The most prominent features detected from the transit spectra of exoplanets are the Na I and K I doublets at 589.3 and 766.4 nm. These metals play a significant role in exoplanetary atmospheres because they ionize readily, thereby producing an extensive ionosphere more like that of a star, rather than Jupiter. Such an ionosphere significantly affects exoplanetary temperatures and circulations. Yet, observations of these signatures are also arguably the most bewildering. Some exoplanets exhibit only the Na feature, others only the K feature and some display both signatures. Yet, theoretical models indicate that exoplanets with temperatures above $\sim$1000 K, contain enough Na and K to display both alkali doublets. Past studies suggest that this discrepancy between the current observations and theoretical predictions arise from systematic errors derived from the terrestrial water and interstellar medium features, and insufficient information on the spectral continuum and the definition of the alkali band wings. Here we propose observations of the exoplanetary K and Na doublets that handle all known sources of the systematic errors. We target the exoplanet XO-2b, because its host star, XO-2N, has a binary companion, XO-2S, with the same brightness and stellar type, which, recorded simultaneously, serves as a reference star for removing terrestrial water and interstellar features Observations recorded on LBT/MODS in dichroic mode have the unique capability to simultaneously record high SNR measurements over the entire 0.32–1.0 μm region as needed to treat the systematic errors, constrain the continuum and the planet's 10-bar radius, and define the wings of the Na and K doublets. We expect to measure alkali abundances to within a factor of 4, and thereby define an exoplanetary ionosphere.

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	LBT	f/15	MODS			1	grey	Jan-Feb	Jan-Feb	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: This program requires the dates specific to the transit of XO-2b in front of its host star. In order of preference these dates are, in Arizona time, Jan 4, Feb 7, Jan 25, and Feb 28 as listed below.

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	XO-2N (TYC 3413-5-1)	07:48:06.46	+50:13:32.90	B=11.91, V=11.25, R=10.8, G9V
2	XO-2S (TYC 3413-210-1)	07:48:07.48	+50:13:03.29	B=12.05, V=11.20, R=10.7, G9V
3	HD 233451	07:47:52.41	+50:12:41.08	B=10.51, V=10.19, G0
4	TYC 3413-187-1	07:48:12.374	+50:17:56.93	B=10.51, V=12.06, n/a
5	TYC 3413-252-1	07:47:36.880	+50:08:22.41	V=12.46, n/a

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
Robert Zellem	Caitlin Griffith		no	no

Scientific Justification

Unlike our Jovian planets, "hot Jupiter" exoplanets are predicted to have high abundances of Na and K [2, 3, 9, 10]. The low ionization potentials of these alkali metals imply large stratospheric electron densities of $\sim 10^9$ cm^{-3} due to photo-ionization [12]. These densities are orders of magnitude larger than those in any ionsphere in the solar system. The resulting strong ionization state significantly affects the thermal structure and circulation through ohmic dissipation and ion drag [15, 18, 11], and gives rise to an atmosphere with stellar and planetary attributes.

The most evident features in optical transit spectra of exoplanets are the ideal probes of exoplanetary ionization states. Sodium and potassium, the dominant sources of electrons in the lower atmosphere, exhibit doublets at 589.3 and 766.4 nm, respectively. In fact, it was through the detection of Na I in HD 209458b that an exoplanetary atmosphere was first detected [2]. However, further measurements of these alkali features led to puzzling results. Some exoplanets (e.g., XO-2b [23, 24]) indicate the presence of both Na and K, as predicted, while others indicate only K I or only Na I (e.g., HAT-P-1b [13]). Yet models that consider thermochemical equilibrium, photochemistry and condensation clearly indicate that these alkali metals should be in atomic form for temperatures greater than $\sim$1000 K [32]. Therefore both the Na I and K I doublets should theoretically be observed in these exoplanetary spectra even considering a range of elemental abundances. Thus models and observations, taken together, indicate the need to improve the techniques for observing and interpreting these features.

The conflicting information on the alkali content of exoplanets and the puzzling suite of signatures stem from a number of effects. Alkali metals have been identified though the detection of the peak fluxes in the doublets, which, towering over the wings, are saturated, and therefore do not depend sensitively on the abundances. By contrast, the line wings, which are highly sensitive to the alkali abundances, have been measured only once; HST/STIS observations of one of the most extensively measured exoplanet, HD 209458b, define the wings of the Na I line, although not K I [22], and indicate a smaller abundance of Na than predicted by photochemical models [12]. These space-based measurements are affected by systematic errors and by the absorption of Na I and K I due to the interstellar medium, which might explain the lack of detection of the K I doublet.

Additional sources of errors can account for the disparate alkali measurements of exoplanetary atmospheres. The interpretation of the data requires constraints on the 10-bar radius [6], and on clouds [e.g., 16, 22, 17], which can affect the data interpretation by essentially truncating the wings' signatures [4]. This information can be determined from the blue continuum. Observations of the faint signal of exoplanets are also compromised by small systematic errors (e.g., CCD non-linearity [25]), which are specific to each instrument. In addition, the possibility of stellar variability (e.g., from star spots [29]) and exoplanetary variability (e.g., from clouds [14]) further complicate the interpretation of transit data. As spectroscopic measurements of exoplanets improve, it is becoming increasingly evident that variations are common to many if not most exoplanetary systems. Observations of XO-2b suggest small variations in the light curve depth less than 1 mmag [7]. These variations, if they are inherent of the planetary system, indicate that data taken on one night cannot necessarily be interpreted with data from another night. Also, for ground-based observations, terrestrial water blends with the alkali stellar and planetary features [30], requiring the elimination of these effects to better than the 0.1% level.

Here we propose observations of the exoplanet XO-2b with LBT/MODS in dichroic mode to measure the Na I and K I doublets, while treating the sources of errors indicated by prior observations. To characterize exoplanetary ionospheres, observations need to define both the wings of the Na I and K I lines as well as the continuum absorption and the planet's radius at a reference pressure. In addition they must constrain the effects due to terrestrial and interstellar absorption and systematic errors, and take into account the fact that the system may be inherently variable. These requirements determine our approach. The Large Binocular Telescope operating in dichroic mode is the only configuration that can simultaneously measure the entire 0.37–0.9 μm spectral region at high enough precision, wavelength coverage and sampling to characterize both of the Na and K wings, the continuum, and the spectral region (0.37–0.47 μm) that reveals the presence of clouds, if present, and the 10-bar radius (Fig. 2). This setup ensures that the observations are recorded with the same baseline R_P/R_S level and thereby not affected by any inherent variability in the exoplanetary system.

Absorption by Earth's atmosphere and the interstellar medium are treated by the selection of the exoplanet. We target XO-2b, a Jupiter-sized body that orbits a K0V star at a distance of 0.0369 AU and a period of 2.6 days [1]. This relatively bright system (V=11.24) is selected because it uniquely has a binary star, XO-2S, 31 arcsec away that is of the same stellar type and brightness as the target host star, XO-2N. The binary companion XO-2S serves as an ideal reference star. Simultaneous observations of the host star, XO-2N and reference stars (Table 1), particularly XO-2S, track the variable effects of the terrestrial atmosphere and instrument systematics, such as the pointing-induced errors and airmass variations, throughout the night. The binary companion, XO-2S, also eliminates interstellar medium absorption, since it samples the same column of the interstellar medium as does the host star [27,26]. While the interstellar absorption is not expected to change during the observations, any measurement of a non-binary reference star can have different interstellar lines because it samples a different path and distance through the interstellar medium [30]. An additional advantage of XO-2b is that it is hot enough that, based on observations and theory, clouds are expected to be at higher pressures than those sampled here, or at most optically thin. The proposed observations remove systematic uncertainties that plagued earlier investigations of the alkali features, thereby enabling a study of an exoplanetary ionosphere, and more generally exploring the capabilities of ground-based spectroscopy of extrasolar planets. Based on a full radiative study of the expected LBT/MODS dichroic spectrum (Fig. 2), we predict that LBT/MODS will indicate the abundances of Na and K to with a factor of 4, a precision that will enable a better understanding the deep ionospheres of extrasolar planets and their joint stellar and planetary nature.

[1] Burke et al. 2007, ApJ, 671, 2115
[2] Charbonneau et al. 2002, ApJ, 568, 377
[3] Fortney et al. 2003, ApJ, 589, 615
[4] Fortney et al. 2008, ApJ, 678, 1419
[5] Fortney et al. 2010, ApJ, 709, 1396
[6] Griffith 2014, Royal Soc., 372
[7] Griffith et al. 2014, submitted
[8] Henry 1999, PASP, 111, 845
[9] Koskinen et al. 2013, Icarus, 226,1678
[10] Koskinen et al. 2013, Icarus, 226,1695
[11] Koskinen et al. 2014, Exoclimes
[12] Lavvas et al. 2014, Exoclimes
[13] Nikolov et al. 2014, MNRAS, 437, 64
[14] Parmentier et al. 2013, A&A, 558, A91
[15] Perna et al. 2012, ApJ, 751, 59
[16] Pont et al. 2008, MNRAS, 385, 109
[17] Pont et al. 2013, MNRAS, 432, 291
[18] Rauscher & Menou 2012, ApJ, 745, 78
[19] Teske et al. 2013, MNRAS, 431, 1669
[20] Thatte et al. 2011, A&A, 523, A35
[21] Turner et al. 2013, MNRAS, 428, 678
[22] Sing et al. 2008, ApJ, 686, 667
[23] Sing et al. 2011, A&A, 527, A73
[24] Sing et al. 2012, MNRAS, 426, 1663
[25] Snellen et al. 2008, A&A, 487, 357
[26] Stevenson et al. 2014, AJ, 147, 161
[27] Waldmann et al. 2012, ApJ, 744, 35
[28] Waldmann et al. 2013, ApJ, 766, 7
[29] Winn 2010, arXiv, 1001.2010
[30] Wood et al. 2011, MNRAS, 412, 2376
[31] Zellem et al. 2014, In Press.
[32] Lodders 1999, 519, 794
[33] Swain et al. 2010, Nature, 463, 637

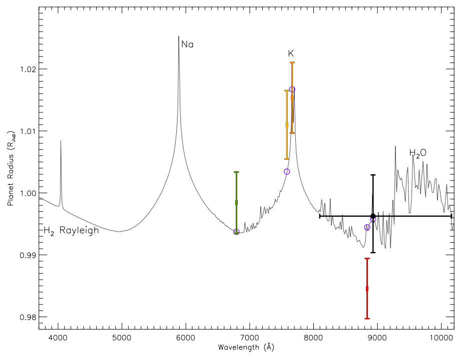

Figure 1: (*Left*) Observations that led to the detection of potassium in XO-2b's atmosphere (orange, black, green and red points) are shown with an isothermal 1500 K model [23]. The observations proposed here improve upon this and other prior work [24], which had significant slit losses, by covering a larger wavelength extent, at a higher wavelength sampling and with the high SNR needed to define the band wings and the continuum, and by adopting large aperture masks to prevent slit losses.

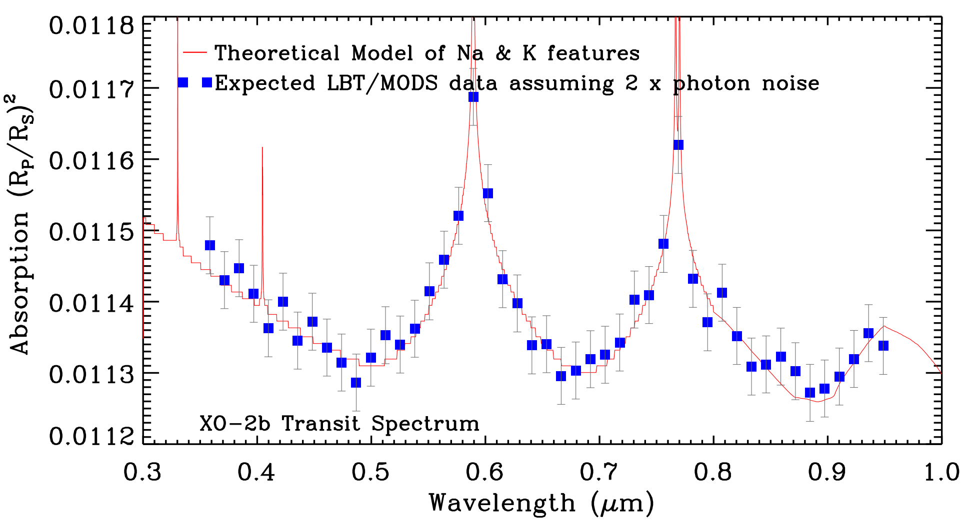

Figure 2: Simulation of the expected spectra of XO-2b from LBT/MODS observations. Errors are estimated conservatively to be 2× photon noise (shown by error bars) based on prior exoplanetary observations, e.g. [2,1,26]. The points indicate the predicted spectral sampling after binning with random noise added to simulate counting statistics and systematic errors. The red line indicates the noise-free atmospheric model, which includes the effects of photochemistry and assumes a cloud-free atmosphere, and which is at a higher spectral resolution than the proposed observation (thereby revealing even the weak alkali features). Given the temperature of the planet, thick clouds are unexpected and would be interesting in themselves. Instead, we expect the 0.37–0.47 μm Raleigh slope caused by H_2 scattering to define the temperature and 10-bar radius. As demonstrated here, the proposed LBT/MODS observations can characterize simultaneously the Na and K band wings and the 0.37–0.9 μm continuum at an unparalleled high precision.

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)***

XO-2b's primary transit is recorded with a time sequence of spectral images of the host star and calibration binary companion and other field calibration stars before, during and after the transit. The transit duration of XO-2b is 162 minutes. Roughly an equal amount of time, if possible, before and after the transit is allotted to establish the out-of-transit baseline to help characterize and remove systematic errors. Therefore each transit measurement requires a total observation time of at least 7 hours on target, including in and out-of-transit observations. Our prior measurements of exoplanetary transits indicate that observations must be recorded when the target is above 35° altitude. As XO-2b has a declination of 50°, there are only 4 nights when the source is above 35° altitude with a sufficient amount of out-of-transit baseline. Observational information regarding these transits are detailed in Table 1.

According to the MODS1 Instrument Manual, we estimate that a 30 second integration time of XO-2 (V=11.24) with 2x2 binning (to reduce the read time) yields 222,000 e^- per image for each exposure, when binned along the spatial direction of the detector. Considering the 0.012 arcsec/pixel scale, for 2x2 binning and a minimum seeing of 0.8 arcsec, each binned pixel receives ~1/3 of the total stellar image, yielding an electron count per pixel (~222,000/3 = 74,000 e^-/pixel), which is well within the ADC Saturation limit of 163,838 electrons (65535 ADU × 2.5 e-/ADU), as well as the linear response regime of the CCD detector.

A 30 sec exposure time yields a SNR range of 196–333 for each image of XO-2b, i.e., after integrating all the spatial pixels that define the image of the star on the detector. Assuming a readout time of 55 secs, resulting in an overhead of 55/(55+30)= 65%, we will obtain 114 exposures during XO-2b's 2.6 hour transit, yielding a measurement of XO-2b's transit depth with a SNR of 2977–5048 and an uncertainty of $2.\times10^{-4}$–$3.\times10^{-4}$ per wavelength channel. We will then bin 100 pixels in wavelength-space to end up with 2750/100 = 27 new wavelength bins to further increase the SNR to 29,777–50,481, resulting in a final, binned uncertainty on the transit depth of $2 \times 10^{-5} - 3 \times 10^{-5}$ assuming the photon noise limit. Based on previous ground-based optical spectroscopy (e.g. [21,26]), we predict that LBT/MODS will be capable of obtaining a precision of $2\times$ the photon noise limit, resulting in a final transit uncertainty of $4 \times 10^{-5} - 6 \times 10^{-5}$. Figure 2 shows an example of the expected LBT/MODS spectrum.

We will use both standard IRAF extraction techniques as well as in-house procedures to treat the raw data and extract the time-varying flux of the target and comparison stars. Systematic errors will largely be removed by dividing XO-2b's lightcurve with that of its binary companion, XO-2S, and if necessary a combination of other bright comparison stars in the field. Any residual systematics will be treated with an array of procedures that we have successfully used to extract the planetary signal in prior data sets. These procedures include the Self-Coherence Method, Independent Component Analysis (ICA), and Principal Component Analysis (PCA) (e.g., [33], [27], [28], [31]).

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 the first time that we submit a proposal to LBT for this project. We require only 1 night to complete this project.

This strategy of the proposed observations was formulated based on the team's prior observations, which include ground-based monitoring of XO-2b with Greg Henry and extensive previous measurements of XO-2b with the Kuiper 61" [6,7].

The following table lists dates for which the exoplanet XO-2b transits its host star. These nights **listed in order of preference** are the only opportunities for the observation of this target.

Table 1: **Requested Primary Eclipse Dates & Times (ARIZONA TIME)**

Target	**Date Requested** start night	**Ingress** local time	**Egress** local time	**Platform**
XO-2b	04-Jan	23:10	01:52	LBT/MODS
XO-2b	07-Feb	23:18	02:00	LBT/MODS
XO-2b	25-Jan	21:24	00:06	LBT/MODS
XO-2b	28-Jan	21:33	00:15	LBT/MODS

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)***

In preparation for these observations, we have been measuring the photometric U- and B-band transits of XO-2b and other exoplanets with the University of Arizonas 61 Kuiper telescope and Mont4k CCD in Tucson, Arizona [6,7]. We have devised an observation and reduction technique that allows us to measure XO-2bs primary transit with a precision of 2x the photon noise. Since stellar variability can influence the retrieved transit depth, we have also been monitoring XO-2b's brightness since the fall of 2014 with the Tennessee State Universitys 0.36 and 0.61 meter automated imaging telescopes (AIT) at Fairborn Observatory in southern Arizona [8]. Both observations indicate consistently that XO-2N exhibits stellar variability, which although very subtile would add significant errors if one tries to piece together spectra from separate times.

Our group has also determined the metallicities, effective temperatures and surface gravities of the host star (XO-2N) and its binary companion (XO-2S), as part of a larger effort to understand the connection between the host stars composition and that of their planets [19].