OBSERVING REQUEST
University of Arizona Observatories

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

Exoplanet atmospheres at high resolution

P.I.: Ian Crossfield (LPL; *ianc@lpl.arizona.edu*; 949.923.0578)

CoI(s): J. Birkby (CfA), T. Barman (LPL), D. McCarthy (SO), D. Charbonneau (CfA), M. Lopez-Morales (CfA)

Abstract of Scientific Justification

We propose to study the atmosphere of three non-transiting hot Jupiters as part of our UA+CfA collaboration using high-resolution (R=30,000) time-series spectroscopy from ARIES+MMT AO. With sensitivity sufficient to detect H2O, CO, CO2, and CH4 in the planet's atmosphere, we will measure the first precise C/O ratio for these exoplanet atmospheres and place unprecedented constraints on the formation mechanism and birth location of hot Jupiters in protoplanetary disks. The combined resolution and wide simultaneous wavelength coverage of ARIES/MMT are unparalleled, making this the superlative instrument for such observations. These observations will demonstrate that the MMT has a major long-term role to play in the rapidly rising field of exoplanet atmosphere characterization, and provide key inputs into the design of analogous instruments on the GMT.

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	MMT	f/9	ARIES	*		7	bright	Sep–Oct	Sep–Oct	no	no

Scheduling constraints and unusable dates *(up to 4 lines)*: We require nights when the planets are near quadrature to maximize their nightly Δv and permit optimal separation of star and planet spectra. We prefer nights when the planets' hotter day sides are visible in order to increase the expected planet/star contrast ratio. During bright time, the optimal windows at MMT are Sep 27–Oct 7 and Oct 17–Oct 23.

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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	ups And b	01h36m47.8s	+41:24:19.6	R=3.6,K=2.9
2	tau Boo b	13h47m15.7s	+17:27:24.9	R=4.1,K=3.4
3	HD 217107	22h58m15.5s	-02:23:43.4	R=6.0,K=4.5

Approval for Instrument Use from PI: see attached email from D. McCarthy

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

Scientific Justification

Hot Jupiters (HJs) provide a crucial training ground for the observational techniques that will ultimately enable measurements of the chemical composition of nearby Earth-like planets during the era of the GMT (Snellen et al. 2013, Rodler & Lopez-Morales 2014). Moreover, the composition and structure of the atmospheres surrounding these hot, giant planets provide a fossil record of their primordial origins, thereby elucidating the formation and evolution of the universal population of exoplanets. Their chemical composition, in particular their carbon-to-oxygen ratios (C/O), can be directly linked to where and how the planet formed in its protoplanetary disks, owing to the different condensation temperatures of molecular snow lines (e.g. Oberg et al. 2011; see Fig. 1, left). Furthermore, the relative abundances of the major C- and O-bearing molecules in these atmospheres such as H2O, CH4, CO2, and CO strongly depend on both the C/O ratio and the vertical temperature profile of the atmosphere (e.g. Moses et al. 2013; Madhusudhan, 2012), giving insight into their structure and active dynamical processes (e.g. Snellen et al. 2010).

We request 7 nights with MMT/ARIES to determine the composition, C/O ratio, and atmospheric structure of three non-transiting hot Jupiters to begin building a statistically significant sample of planetary measurements. We use a ground-based, near-IR, high-resolution spectroscopy approach that been pioneered to great effect (e.g., Crossfield et al. 2011, Birkby et al. 2013, 2014, Rodler, Lopez-Morales, & Ribas 2012, and many others). All three planets are targets of our ongoing Spitzer/IRAC observations of these planets' thermal phase curves (Spitzer PIDs 10078 & 11044, PI Crossfield). Useful in their own right, our requested ARIES observations will also directly support our approved Spitzer program.

Our observing technique unambiguously detects molecular species in HJ atmospheres by spectrally resolving the forest of molecular lines in the planet's spectrum. We trace out the large radial velocity shift of the planet's spectrum (RV$\sim$km/s) over several nights, while the spectral lines from the host star (RV$\sim$m/s) and Earth's telluric lines remain essentially stationary. The star-planet system becomes a double-lined spectroscopic binary, as shown in Fig. 2. The stellar mass is known, so we can determine both the mass of the planet and its inclination along our line-of-sight.

Our approach offers an efficient ground-based alternative to the sometimes ambiguous space-based, low-resolution, transmission and emission spectroscopy techniques (e.g., Tinetti et al. 2007; Swain et al. 2008; Grillmair et al. 2008), where the goal is to measure changes in the host star flux that are typically orders of magnitudes smaller than the instrumental systematics that have been shown to plague such observations (e.g. Gibson et al. 2011, 2012; Birkby et al. 2013). Furthermore, our technique can characterize non-transiting systems and so a much larger planet population can be targeted.

The technique is only sensitive to the relative depths of the individual spectral lines due to the unknown planet continuum level. Composition and thermal structure are thus somewhat degenerate for measurement in a narrow wavelength range. The broad wavelength coverage of ARIES mitigates this limitation by both simultaneously detecting multiple molecules in a single data set and by detecting features from single molecules over large wavelength regions (CO above 2.3 μm, H_2O below). The unparalleled high dispersion and simultaneous wavelength coverage of ARIES makes it the superlative instrument for our science.

Our targets are the three brightest systems visible in 2015B. One of these, tau Boo b, has been observed previously at the VLT and Keck (Brogi et al. 2012, Rodler et al. 2012, Lockwood et al. 2014), resulting in 6σ detections of CO and H2O. tau Boo is therefore our sample's reference object. No high-dispersion NIR detections have been published for our other two targets, ups And b and HD 217107b, so **our observations will be the first to probe the atmospheric properties of these nearby planetary systems.**

Immediate Objective: Our immediate objective is to measure the atmospheric composition and thermal structure of three hot Jupiters orbiting nearby bright stars: ups And b, tau Boo b, and HD 217107b. Our high-dispersion analysis treats the star-planet systems as double-lined spectroscopic binaries to characterize the planets' spectra. These data will supplement our ongoing Spitzer/IRAC observations of these planets' thermal phase curves (Spitzer PIDs 10078 & 11044, PI Crossfield) to provide an unprecedented view of the interplay between atmospheric circulation, composition, and the planets' formation. More generally, we seek to demonstrate the capabilities of MMT/ARIES for such observations.

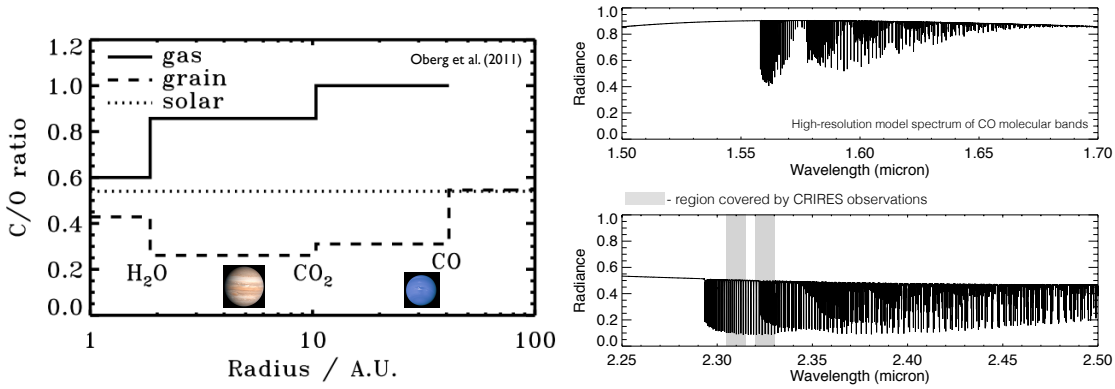

Figure 1: **Left:** The change in the C/O ratio of the gas and planetesimals in a protoplanetary disk in a solar-like system. The further out the planet accretes is gaseous envelope, the higher its C/O ratio. However, if the planet forms instead by stellar-like gravitational collapse, its gaseous component should instead reflect the stellar C/O. **Right:** A high-resolution model spectrum of the CO molecule in the ARIES simultaneous wavelength region. ARIES observes $\sim$7$\times$ as many CO lines as CRIRES (shaded), significantly boosting our sensitivity. The situation is similar for H_2O, which has lines throughout the near-IR. Models will be created by Co-I Barman.

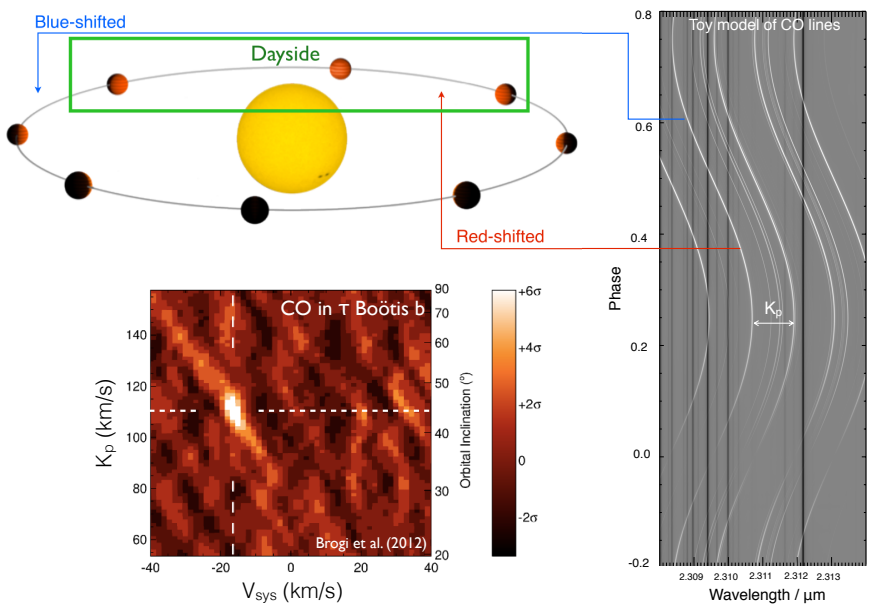

Figure 2: Molecules in exoplanet atmospheres can be identified by directly detecting the RV shift of individually resolved lines in the molecular bands of the exoplanets spectrum at very high-resolution, ($\lambda/\Delta\lambda \sim$ 25 000 – see right and top panels where planetary lines are white and Earth's telluric features are black. The green line marks out the approximate range of phases we aim to observe.). The $\sim$km/s Doppler shift of the planet over a fraction of its orbit allows it to be separated from the essentially stationary stellar lines (Δv $\sim$m/s) and static telluric features of the Earth's transmission spectrum. The tellurics are removed with a PCA-like analysis. By cross-correlating with models across a range of RV semi-amplitude (Kp), the planetary signal can be extracted from the residuals, regardless of the system's inclination, although it must coincide with the total system RV (V_{sys}) to be considered of planetary origin. The bottom-left panel shows cross-correlation values representing our first unambiguous detection of a molecule in a non-transiting planet. The independently measured $V_{sys} = -16$ km/s is marked by the vertical dashed white lines.

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 will use the Arizona Infrared imager and Echelle Spectrograph (ARIES), in conjunction with AO on the MMT, to achieve a spectral resolution of R = 30, 000 and wide simultaneous wavelength coverage ($\sim$ 1.4 – 2.4 μm). This requires the 1" $\times$ 0.2" echelle grating. The observations themselves are simple to execute. Our targets (see target list) will act as the AO guide stars, upon which the loop will be closed at the begin of the observations. We will then take consecutive exposures of the target without interruption until it reaches airmass > 2. We will do this for the entire night, covering orbital phases between $0.3 < \phi < 0.7$, when the planets' dayside hemispheres are turned towards us. Our requested time blocks ensure that on each night at least one of our targets fulfills these requirements.

On each night, the planet's RV will change by several tens of km/s. Our individual exposures will be tailored such that the signal-to-noise in the continuum of the star is S/N$\sim$200, which our experience shows to be sufficient for our proposed technique. The end result will be a time-series of high-resolution spectra ($\sim$ 200 per night) over which the planetary spectrum shifts significantly, while the telluric and stellar features of the hot host star are stationary.

We base our sensitivity estimates from the past successful observations of tau Boo b with the now-decommissioned CRIRES/VLT (R = 100 000, 8 m, Brogi et al. 2012) which result in a 6σ detection of CO and H2O in two nights. The ARIES 1.4–2.4μm region covers a $\sim 7\times$ broader wavelength range than does CRIRES (see Figure 1, right), increasing our S/N by $\sqrt{7}$ $\sim$2.5. However, MMT's smaller diameter compared to VLT (8.1m/6.5m $\sim 1.25\times$ smaller) and lower resolution ($\sqrt{100000/30000} \sim 1.8\times$ smaller) decrease our sensitivity by 1.25×1.8, so ARIES' final sensitivity is essentially the same as that of CRIRES. We therefore require a similar amount of time (two nights) per planet as was needed for the CRIRES/VLT observations. With three planets and typical Arizona weather, we therefore require a minimum of seven nights to secure detections for our three planets.

The wide ARIES wavelength range enables not just the detection of CO and H2O, but also new molecules including CH4, CO2, HCN and possibly acetylene (C2H2). Consequently, our observations will allow us to i) measure the relative abundances of the major C and O molecules to within an order of magnitude, and hence ii) provide a robust, precise C/O ratio to study its link to the planet's formation mechanism and birth location, as well as iii) constrain the temperature structure of the atmosphere to an unprecedented level, including the presence of a stratosphere, which appears as emission lines rather than absorption lines, and clouds, which may act to suppress the expected lines depths at short wavelengths. Our goal is not only to characterize the atmosphere of these planets, but to cement the role of the MMT as a key observatory in the rapidly expanding field of exoplanet characterization. No other existing instrument can currently match ARIES/MMT in both resolution and infrared wavelength coverage which are crucial to this technique. Its closest competitor is NIRSPEC/Keck. The proposed observations here will prove the ability of ARIES in exoplanet atmosphere characterization. When successful, this effort will pave the way for a large, long-term program to perform a complete census of the diverse properties of hot Jupiter atmospheres and will provide crucial input into the design of the GMT's planned analogous instrument, GMTNIRS.

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 proposal is part of a joint program between PI Crossfield (UA/LPL) and Co-I Birkby (Harvard/CfA) to maximally leverage the capabilities of ARIES to characterize hot Jupiter atmospheres at unprecedented precision. Co-I Birkby received time from the Harvard TAC in 2015A but was weathered out; she submitted a complementary 2015B proposal at Harvard for observations of additional targets.

PI Crossfield is leading the Spitzer/IRAC observations of our targets to obtain thermal phase curves, measure dayside and nightside temperatures, and constrain global circulation and heat recirculation. These ARIES observations provide an essential complement to the Spitzer data by providing molecular abundances and thermal structure in addition to the Spitzer temperature measurements. Co-I Birkby is leading the ARIES research efforts, building on her experience with this observing technique at VLT/CRIRES (Birkby et al. 2013, 2014).

Co-I Barman will generate the high-spectral-resolution model planetary spectra needed for our cross-correlation analyses. Co-Is Lopez-Morales and Charbonneau will help with the data analysis and interpretation.

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**)*

To date, no UAO time has been awarded for this project.

Co-I Birkby received a 3-night MMT/ARIES allocation from the Harvard MMT TAC to observe tau Boo b in 2015A, but all nights were weathered out.

PI Crossfield has been awarded 1 night of LBT/LMIRCam AO observations in 2015A; observations are scheduled for June. He has been awarded time on numerous large telescopes resulting in high-impact publications. Among many others, these include the high-dispersion NIR Keck/NIRSPEC observations of sub-Neptune GJ 1214b, which are directly relevant to this proposal (Crossfield et al. 2011); high-dispersion NIR VLT/CRIRES Doppler Imaging of the nearby brown dwarf Luhman 16B (Crossfield et al. 2014, *Nature*); and medium-resolution Keck/MOSFIRE spectroscopy of the transiting hot Neptune GJ 3470b (Crossfield et al. 2013).