OBSERVING REQUEST
University of Arizona Observatories

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

Chemical Composition of a Cool, Cloud-Free "Hot Neptune"

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CoI(s): T. Barman (LPL), A. Skemer (SO), C. Kulesa (SO), D. McCarthy (SO)

Abstract of Scientific Justification

Systems of small, cool planets represent the typical end-products of planetary formation. By measuring these planets' atmospheric compositions, we can directly inform theories of planet assembly and migration. However, observations of sub-Jovian planets have revealed mostly featureless transmission spectra – precluding measurements of atmospheric composition. The 800 K hot Neptune HAT-P-11b shows clear evidence for H_2O absorption, and so this planet offers the rare opportunity to probe the atmospheric composition of a relatively cool, sub-Jovian exoplanet. We propose to measure CO in HAT-P-11b's atmosphere and confirm the H2O detection using two nights of MMT/ARIES high-dispersion infrared spectroscopy.

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/10.3	ARIES	*	*	3	bright	Jun–Jul	Jun–Jul	yes	no

Scheduling constraints and unusable dates *(up to 4 lines)***:** We are observing a transiting planet, and transits at good airmass occur only on select nights. In 2015A, these transits occur on June 7, July 16, and July 22 (all dates in Arizona Time). A single night will allow us to detect the presence of CO and perhaps H_2O, but multiple nights will let us measure the relative abundances of the different molecules and provide greater confidence in our result.

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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	HAT-P-11	19:50:50.1	+48:04:49.1	V=9.6, K=7.0
2	51 Dra	19:04:55.2	+53:23:48.0	A0V calibrator; V=5.4, K=5.4

Approval for Instrument Use from PI: see attached e-mail 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

Both the Kepler mission and radial velocity surveys demonstrate that the occurrence frequency of planets increases toward lower masses and temperatures (Howard et al. 2010, 2011, Bonfils et al. 2013). Systems of small, cool planets represent the typical end-products of planetary formation. To the extent that these natal processes impact a planet's present-day atmospheric composition, measurements of this composition directly inform theories of planet assembly and migration. Considering their rarity, Jovian-scale exoplanets – studies of which currently dominate our understanding of exoplanetary atmospheres – may ultimately provide less information on typical planet formation processes.

Most small, cool planets currently known do not lend themselves well to the observations needed to determine their atmospheric compositions. Sub-Neptune planets are too faint to study in detail via high-contrast AO imaging; the hundreds discovered by RV typically do not transit; the thousands discovered by Kepler mainly orbit only faint stars. A few transit bright targets, and so their atmospheric composition can be probed via transmission spectroscopy: measuring the absorption spectrum of the planet's limb when it transits its host star. But the few well-studied low-mass planets have revealed frustratingly featureless transmission spectra, indicating that optically thick aerosols (clouds or haze) are common on such worlds and precluding any detailed atmospheric measurements (Bean et al. 2010; Crossfield et al. 2011, 2013; Kreidberg et al. 2014; Knutson et al. 2014).

The hot Neptune HAT-P-11b ($4.3R_\oplus$, $26M_\oplus$, $\sim$800 K; Bakos et al. 2010) is an exception and offers **the rare opportunity to probe the atmospheric composition of a relatively cool, Neptune-mass exoplanet.** Transit observations with the HST/WFC3 grism show clear evidence of absorption by H_2O (see Fig. 1; Fraine et al. 2014), consistent with a H_2-dominated atmosphere. However, with WFC3's limited wavelength range it cannot probe the planet's carbon chemistry. We propose to measure the atmospheric composition of HAT-P-11b, especially the dominant carbon-bearing species, by adapting our prior Keck/NIRSPEC analysis of cool super-Earth GJ 1214b (Crossfield et al. 2011). **We request three nights with MMT/ARIES for three transits of HAT-P-11b to detect CO, H_2O, and possibly CH_4 in this planet's atmosphere.** Available nights in 2015A are June 7, July 16, and July 21 (all dates refer to the beginning of the night, in Arizona). ARIES is the ideal instrument because with it we can detect individual molecules at high dispersion.

Since the first detection of an exoplanet's atmosphere (Charbonneau et al. 2002) numerous hot Jupiters have been studied via the emission or transmission of their atmospheres. This has led to robust detections of numerous atomic and molecular species (Charbonneau et al. 2002, Barman 2007, Snellen et al. 2010), high-altitude hazes (Pont et al. 2008, 2013), and a diverse range of atmospheric circulation patterns (Knutson et al. 2007, Crossfield et al. 2010) and albedos (Rowe et al. 2008, Demory et al. 2013). Studies of these hot Jupiters continue to fuel the ongoing revolution in the field of externally irradiated giant planet atmospheres.

Interior models suggest that hot Jupiters and smaller planets such as HAT-P-11b represent distinct planet formation pathways. Hot Jupiters are composed overwhelmingly of H_2 (Fortney et al. 2007); Neptune-mass planets contain H_2 but ices and/or rocks also make up a large fraction of the interior (Adams et al. 2008). Furthermore, short-period Neptune-sized planets occur around $\sim$4% of stars (vs. $\sim$0.1% for hot Jupiters; Howard et al. 2012, Fressin et al. 2013). Thus these smaller planets represent the primary end products of planet formation. By studying planetary atmospheres, we also inform ongoing studies of planet assembly and migration (Oberg et al. 2011, Ali-Dib et al. 2014) in addition to improving our understanding of planetary atmospheres.

As described above only a few planets substantially smaller and cooler than hot Jupiters have been subjected to detailed scrutiny – of these, only our target exhibits spectral features. The best well-known of the other targets is GJ 1214b, which has the most complete and most precise transmission spectrum of any extrasolar planet (e.g., Bean et al. 2011, Kreidberg et al.,2014); our team used Keck/NIRSPEC to obtain the first NIR spectroscopic observations of this object (Crossfield et al. 2011). All observations of GJ 1214b indicate a featureless transmission spectrum, caused by a high-altitude haze layer of unknown composition (Morley et al. 2013, Kreidberg et al.,2014). The same conclusion is also consistent with recent observations of GJ 436b (with HST/WFC3; Knutson et al. 2014) and of GJ 3470b (with Keck/MOSFIRE and LBT; Crossfield et al. 2013; Nascimbeni et al. 2013) – thus optically thick aerosol layers appear to be common around smaller, cooler planets.

Unlike these hazy planets, our target HAT-P-11b exhibits strong absorption by H_2O (see Fig. 1; Fraine et al. 2014) consistent with an atmosphere devoid (or nearly so) of the optically thick hazes that enshroud similar worlds. This welcome development offers the first opportunity to determine the atmospheric composition of an $\sim$800 K Neptune-like planet. By observing transits of HAT-P-11b with ARIES, we can test for the presence of CO and confirm the HST/WFC3 detection of H_2O.

Though we will be most sensitive to CO and H_2O, we might also hope to detect CH_4 absorption in HAT-P-11b's atmosphere. H_2O is the primary oxygen-carrying molecule in a H_2-dominated atmosphere. At the temperature of HAT-P-11b, the dominant carbon-carrying molecule would be CO in a solar-composition atmosphere in chemical equilibrium (Moses et al. 2013). If disequilibrium processes are weak we may expect some residual CH_4 absorption at the strong bandhead at 2.315 μm. A methane detection would mark HAT-P-11b as an object with unique atmospheric chemistry and a high-priority target for future characterization (e.g., with JWST) and so we design our observations to cover the location of the 2.315 μm methane bandhead. Nonetheless our primary goal is to measure CO.

Our goals are achievable with the expertise we have developed in using infrared spectrographs (NIRSPEC, MOSFIRE, OSIRIS, VLT/CRIRES, Subaru/MOIRCS, IRTF/SpeX) to study extrasolar planet atmospheres. Our prior Keck/NIRSPEC program, transit observations of the cool super-Earth GJ 1214b (Crossfield et al. 2011) provided the first clear evidence for a haze-dominated spectrum at K band. The successful detection of CO in HD 209458b using VLT/CRIRES by Snellen et al. (2010) further supports our choice of observing technique. The software tools developed for these previous high-precision infrared observations are directly applicable to the observations we propose, ensuring rapid dissemination of our results.

In conclusion, we request three nights with MMT/ARIES to measure molecular abundances in a cool, Neptune-mass planet via transmission spectroscopy. Our observations can detect CO, H_2O, and perhaps CH_4 and so can robustly discriminate between hazes and a clear atmosphere, and unusual abundance ratios. We observe in the K band, where these molecules strongly influence the spectrum and our experience suggests we can adequately control the systematics. Our observations take advantage of ARIES' high spectral resolution to measure atmospheric parameters at the photon noise limit with minimal reliance on models; such advantages are only offered by high-dispersion transit spectroscopy.

References

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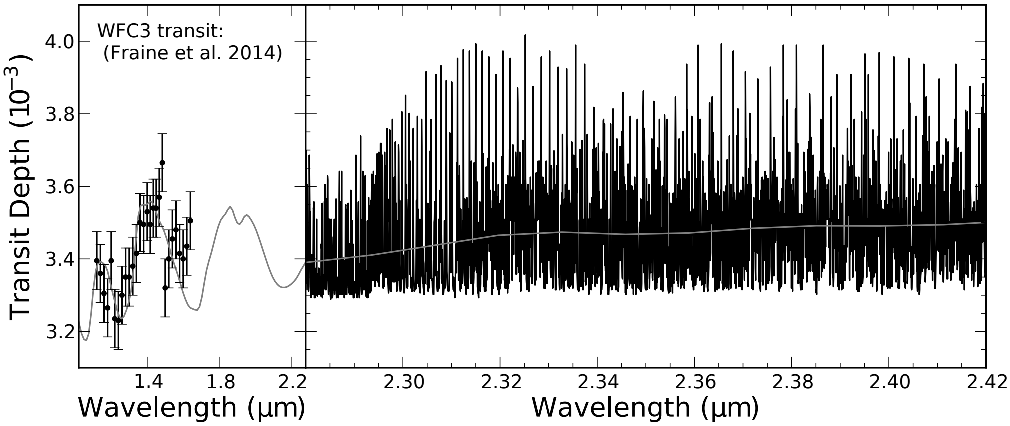

Figure 1: Model transmission spectrum of HAT-P-11b. *Left:* low resolution (gray) with HST/WFC3 measurements (points; Fraine et al. 2014) indicating H_2O absorption. *Right:* at the ARIES resolution of $\lambda/\Delta\lambda = 50,000$ (black; from Co-I Barman), focusing on the CO-dominated wavelengths highlighted by our analysis. Our ARIES observations will a broader wavelength range, but **the wavelengths shown here are sufficient to detect both CO and H_2O** (see Fig. 2).

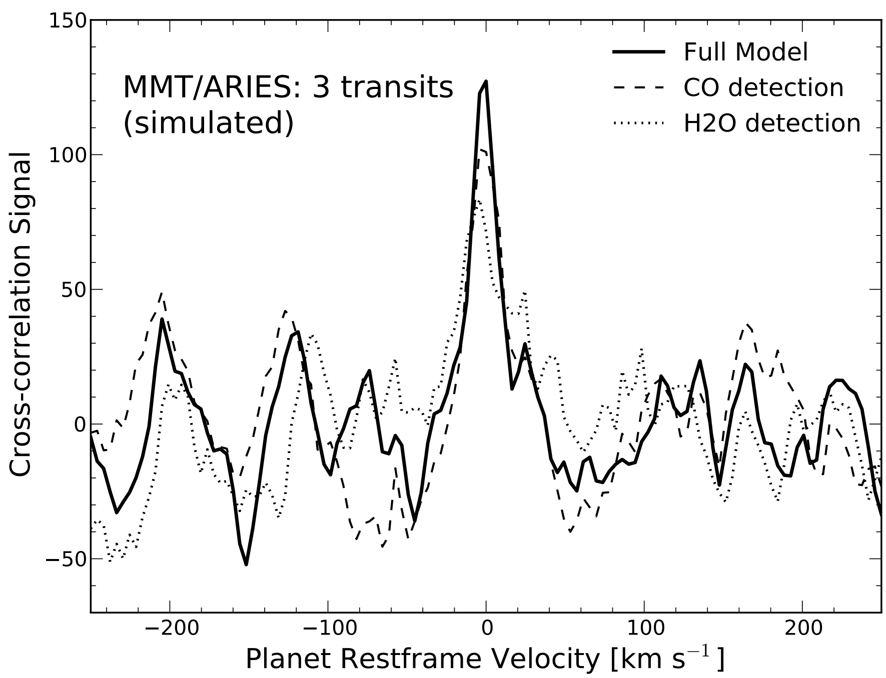

Figure 2: Simulated detection of CO and H_2O in HAT-P-11b's atmosphere via a cross-correlation analysis. The black line shows the signal extracted from two simulated transits with realistic noise sources, using the model in Fig. 1 as a template. The dashed and dotted curves show the detection of independent constituents using independently-computed single-molecule templates: **we will measure CO absorption and confirm the detection of H_2O**. In the unlikely event that instrumental (not astrophysical) effects shape the WFC3 data and HAT-P-11b is instead shrouded in optically thick aerosols, our nondetections of CO and H_2O will reveal this.

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)***

Our approach uses uninterrupted high-dispersion spectroscopy to measure the atmospheric composition of a transiting planet. We obtain our precise sensitivity to HAT-P-11b's atmospheric composition, shown in Fig. 2, by following the successful high-dispersion detection of CO absorption in HD 209458b with VLT/CRIRES (Snellen et al. 2010) and our own Keck/NIRSPEC analysis of super-Earth GJ 1214b (Crossfield et al. 2011).

The high-dispersion technique offers dramatic enhancements over other approaches. With ARIES we **detect individual molecular species** rather than the more degenerate interpretations from low-resolution spectra. Furthermore, high-dispersion methods regularly reach the photon noise limit (Brogi et al., A&A in review) whereas multi-object transit spectroscopy obtains only several times above the photon noise limit (Bean et al. 2013, Crossfield et al. 2013).

We will analyze our data via a cross-correlation analysis, which boosts the S/N, allows us to reject false positives such as telluric and stellar absorption lines, and reveals constituent components of the planet's atmosphere (Fig. 2). During transit the limb of the planet's atmosphere absorbs starlight; this spectroscopic fingerprint is significantly Doppler-shifted by the planet's orbital motion, whereas telluric and stellar spectra are $\sim$stationary, allowing simple yet effective elimination of the latter. During the 2.3 hr transit the planet's radial velocity changes by 14 km/s relative to its host star. This shifts the planet spectrum by $c\Delta\lambda/\Delta v\lambda =$ 2.5 ARIES resolution elements – enough to effectively remove the stellar spectrum without wholly removing the planet's transmission spectrum. All these Doppler effects are encapsulated in the simulation used to produce Fig. 2, demonstrating that **our approach robustly retains exoplanetary signals while rejecting stellar features.**

We observe using the ARIES high-dispersion setting, providing $\lambda/\Delta\lambda = 50,000$. Our main goal is the detection of the CO 2-0 and 3-1 bandheads in addition to numerous H_2O lines (see Fig. 1). The 0.1"×1" slit provides resolution adequate to distinguish HAT-P-11b's Doppler motion, and balances throughput and spectral resolution. We anticipate integration times of 120 s and will acquire $\sim$150 frames per night. This is only a moderate-sized data set, so data volume is not a concern.

Calibrations will consist of a large number ($\sim$100) of flat frames and arc frames (though we will wavelength-calibrate using telluric lines to account for flexure shifts). Low-order sensitivity variations or fringing will be removed via a high-pass filter: high-dispersion transit analyses are sensitive to signals only at high spectral resolution, so this filtering will not degrade our sensitivity. Finally, our transit analysis does not require it, but we will also observe telluric calibration target to facilitate analysis of the planet host star's properties at high spectral resolution.

We constructed a full radiometric instrument model and analysis pipeline for our proposed ARIES observations. Fig. 2 shows the result: a single transit recovers the cross-correlation signal of the input model spectrum (thick solid line). In practice we do not have the benefit of this omniscient viewpoint; the dashed and dotted lines show the result of cross-correlating the simulated observations with templates generated from basic, single-constituent atmospheric models and assuming minimal prior knowledge. Our simulations demonstrate that **we need two transits to obtain a robust detection of the planet's atmosphere.** Further, we note that the exoplanet field is still highly vulnerable to underestimated systematic effects (Hansen et al. 2014)) – observing multiple transits can dramatically increase the perceived significance of our results. To guard against inclement weather, we therefore request 3 nights.

$\boxed{\textbf{Summary of Time Requested and Awarded}}$ *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 small, self-contained project to measure molecular abundances in a planetary atmosphere. To date, no UAO time (or time from other observatories) has been awarded for this project. If successful, we hope it will pave the way for ARIES characterization of many additional transiting exoplanets. The study of these objects is the primary science focus of PI Crossfield, and more generally is a high priority for both Steward and LPL.

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.

PI Crossfield 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).

Subject: Re: ARIES proposals
From: Don McCarthy <dwmccarthy@gmail.com>
Date: 3/20/14 10:24 AM
To: ianc@mpia.de
CC: Craig Kulesa <ckulesa@email.arizona.edu>, Andy Skemer <askemer@as.arizona.edu>, Travis Barman <barman@lpl.arizona.edu>

Hi Ian,

Yes, great. Andy mentioned your interest yesterday and that you are moving soon to LPL. Thanks for working with our undergraduates this past year!

It appears that your star will serve as its own AO guide star.

Andy mentioned that your science goal relates to cloud mapping, hence the high dispersion; correct? What specific wavelength region, spectral/time resolution, and SNR are you hoping for?

Don

On Thu, Mar 20, 2014 at 9:10 AM, Ian Crossfield <ianc@mpia-hd.mpg.de> wrote:

> Hello Don, Craig,
>
> Together with Travis Barman and Andy Skemer (CC'd), I'm planning to put in a proposal for high-dispersion transit spectroscopy with ARIES (I arrive at LPL this summer). The target would be HAT-P-11, a star with K=7, R=9, and a transiting "hot Neptune."
>
> This is my first time proposing for ARIES... What information do you need from me in order to move forward with this idea?
> Thanks!
>
> -Ian
>
> --
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