A Ground-Based Optical Transmission Spectrum Survey of the Atmospheres of Transiting Exoplanets: First Results

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Abstract

We present details of a ground-based program designed to do a comparative analysis of the atmospheres of transiting exoplanets. We have obtained ultra-high signal to noise transmission spectra of four transiting systems. We combine multiple in-transit observations taken by the 9.2m Hobby-Eberly Telescope (HET) and compare directly with out-of-transit observations. Together with high resolution UV spectrographs in space, and infrared photometry, observations in the visible, provide an opportunity to probe important components of exoplanetary atmospheres. We discuss our observations of neutral sodium, the strongest signature in the visible for hot giant planets, and provide a comparative analysis among the exoplanets in our sample. In addition, we discuss prospects for a complete optical transmission spectrum, limits on the extent of any exospheres, as well as, the challenges of such ground-based observations. Measurements, and even upper limits, of atmospheric lines should provide important constraints on models of giant exoplanet atmospheres, including for example, temperature inversions, cloud cover altitudes, atomic and molecular composition, and temperature profiles.

Introduction

Transiting extrasolar planets provide unique opportunities to measure physical properties of exoplanets and their atmospheres that are not accessible for inclined systems. Physical characteristics of a transiting hot-Jupiter atmosphere can be probed by transmission absorption observed against the spectrum of the host star. We present a survey of high resolution, optical, transmission spectra of the brightest exoplanet host stars to investigate the diversity of exoplanetary atmospheres.

Charbonneau et al. (2002) used the STIS spectrograph on HST to detect absorption in NaI caused by the planetary atmosphere of HD209458b during transit. Subsequently, detections have been made from ground-based telescopes in NaI (Redfield et al. 2008; Snellen et al. 2008; Langland-Shula et al. 2009) and KI (Sing et al. 2010; Colon et al. 2010).

Numerous hot Jupiter exoplanetary atmosphere models exist (e.g., Barman 2007; Burrows et al. 2004; Hubbard et al. 2001; Brown 2001; Seager & Sasselov 2000), but have few observable constraints. All transmission models predict strong optical absorption lines, particularly in the alkali metals (e.g., in order of strength, NaI, KI, CsI, and RbI; see Figure 1 below). For this reason our survey focuses first on NaI and KI transmission spectrum features.

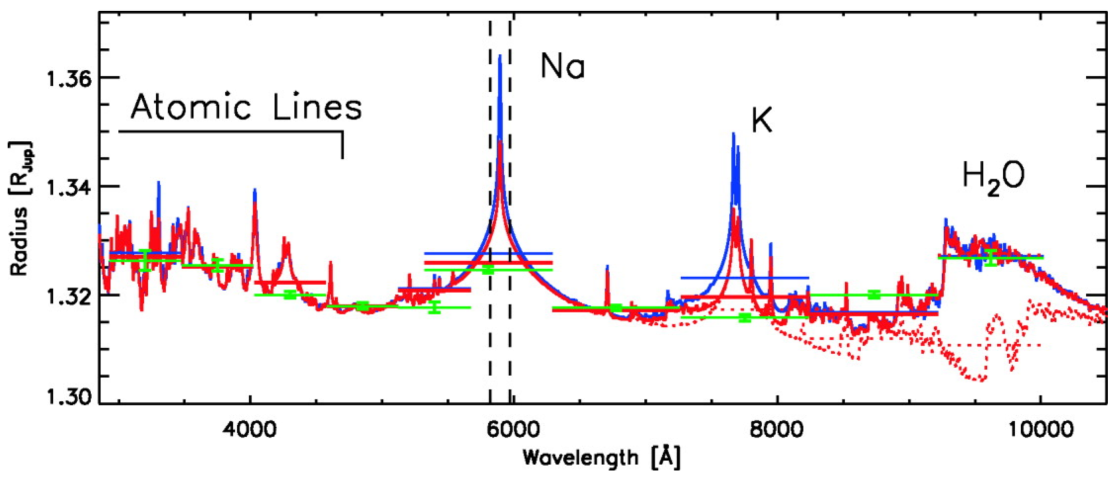

Fig 1. Model from Barman (2007) of HD209458 with low resolution HST spectrum from Knutson et al. (2007). Clearly, the two strongest transitions are sodium and potassium. Our survey observations have a spectral range from 5000-9000 Å, at a resolution of R = λ/Δλ ~ 60,000.

Target Selection

Due to the high signal-to-noise required to detect the weak atmospheric signal, this technique is only appropriate for the brightest of the exoplanetary host stars. That the first detections were of HD209458b and HD189733b is perhaps not a surprise, as these planets orbit the two brightest transit host stars. In addition to these two targets, our survey includes two other planets that orbit bright host stars: HD149026b, which seems to have an anomalously dense core (Sato et al. 2005), and HD147506b, one of the few high eccentricity short-period exoplanets and the brightest transit discovered by the HAT survey; Bakos et al. 2007). Target properties are listed in Table 1, and orbital parameters visualized in Figure 2. This survey represents the largest homogenous sample of visible exoplanetary transmission spectra, and therefore provides a unique opportunity for a comparative atmospheric study.

Table 1 Transmission Spectroscopy Survey Target Properties

Object Name	V (mag)	Spectral Type	Distance (pc)	Period (days)	a (AU)	e	M_p (M_{jup})	R_p (R_{jup})	i (deg)
HD189733	7.67	K0V	19.3	2.2185733	0.0314	0.00	1.15	1.15	85.76
HD209458	7.65	G0V	47.0	3.5247486	0.0475	0.07	0.64	1.38	86.68
HD149026	8.15	G0IV	78.9	2.8758887	0.0429	0.00	0.36	0.61	85.30
HD147506	8.71	F8V	118	5.6334729	0.0674	0.52	8.74	1.19	86.72

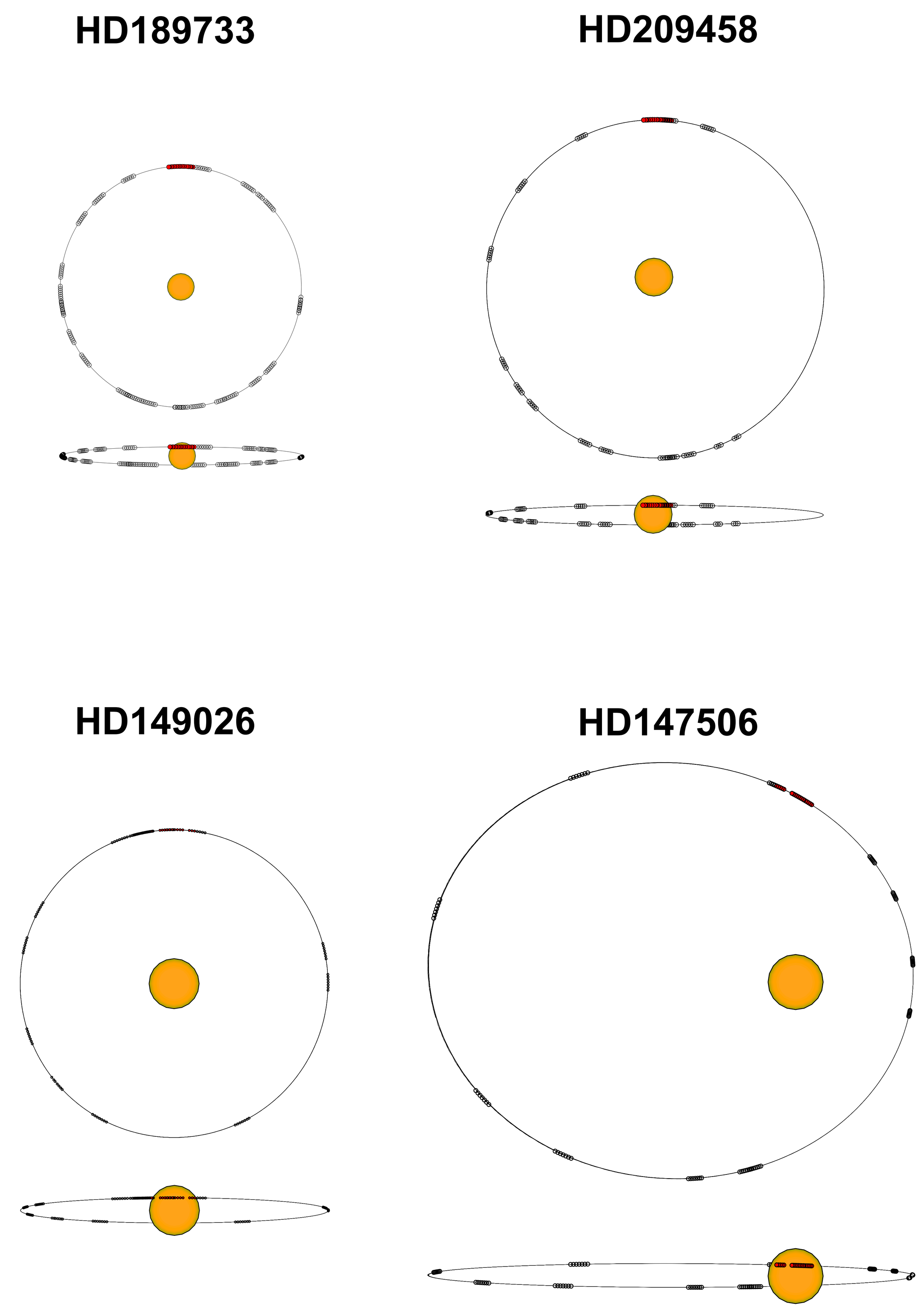

Fig 2. Orbital paths of our exoplanetary targets, to scale. Individual exposures are indicated, with those in red, indicating in-transit exposures.

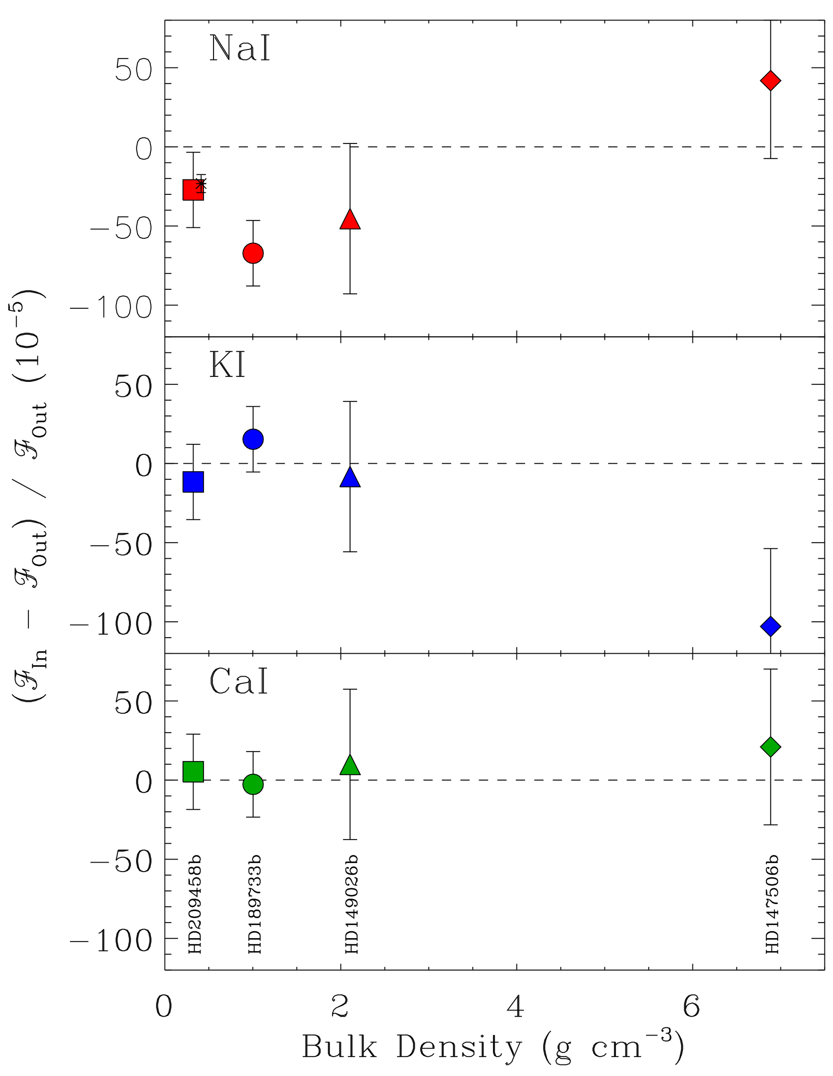

Fig 3. Summary plot of preliminary results from our ground-based optical transmission spectrum survey of the atmospheres of transiting exoplanets. The difference of relative fluxes is shown for all four targets, where a negative number indicates an atmospheric detection due to excess absorption in in-transit observations. Sodium and potassium are predicted to be the strongest features in the visible, while CaI is predicted to have condensed out of these atmospheres and should not show any excess absorption in the transmission spectrum. Hence, it represents a first order check on our data analysis. The Charbonneau et al. (2002) detection of NaI in HD209458b is also shown with a slightly offset asterisk symbol in the top plot. The error bars are a simple scaling from the S/N and are therefore highly preliminary.

Conclusions and Future Work

(1) We have obtained high resolution, high S/N (coadded multiple transit), observations of 4 exoplanetary systems to assemble the largest homogeneous visible survey of exoplanet atmospheres.

(2) A detailed description of the data reduction and analysis is given in our companion poster 2.13 by Adam Jensen et al.

(3) We tentatively detect NaI absorption in 3 of our 4 targets, including HD189733b (initially reported in Redfield et al. 2008). Our measurement for HD209458b matches well the results of Charbonneau et al. (2002) and Snellen et al. (2008).

(4) Our error analysis is in its early stages. We are in the process of running an empirical Monte Carlo analysis, as detailed in Redfield et al. (2008) for all of our targets. Based on our simple scaling, the excess absorption in NaI of two of our targets is only significant to ~1σ.

(5) No excess absorption is detected for CaI, as predicted. This is a strong, first-order, check on our data analysis procedure. We are encouraged that the standard deviation of our CaI measurements is significantly less than our preliminary error bars would indicate, possibly indicating that they are overestimates of the true errors.

(6) Only one of our targets shows substantial excess absorption in KI, the eccentric exoplanet, HD147506b. However, it has the lowest S/N of all of the systems, and based on anomalies in both the NaI and KI transmission spectrum, this measurement will require further scrutiny.

(7) These observations, and the challenges in data reduction and analysis, represent an important step in not only characterizing the atmospheric properties of hot Jupiters, but also strengthen the foundation for similar studies of the atmospheres of terrestrial exoplanets.

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Be sure to visit our companion poster—#2.13 by Adam Jensen et al.