A Ground-Based Optical Transmission Spectrum Survey of the Atmospheres of Transiting Exoplanets: Line Analysis and Future Work

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Abstract

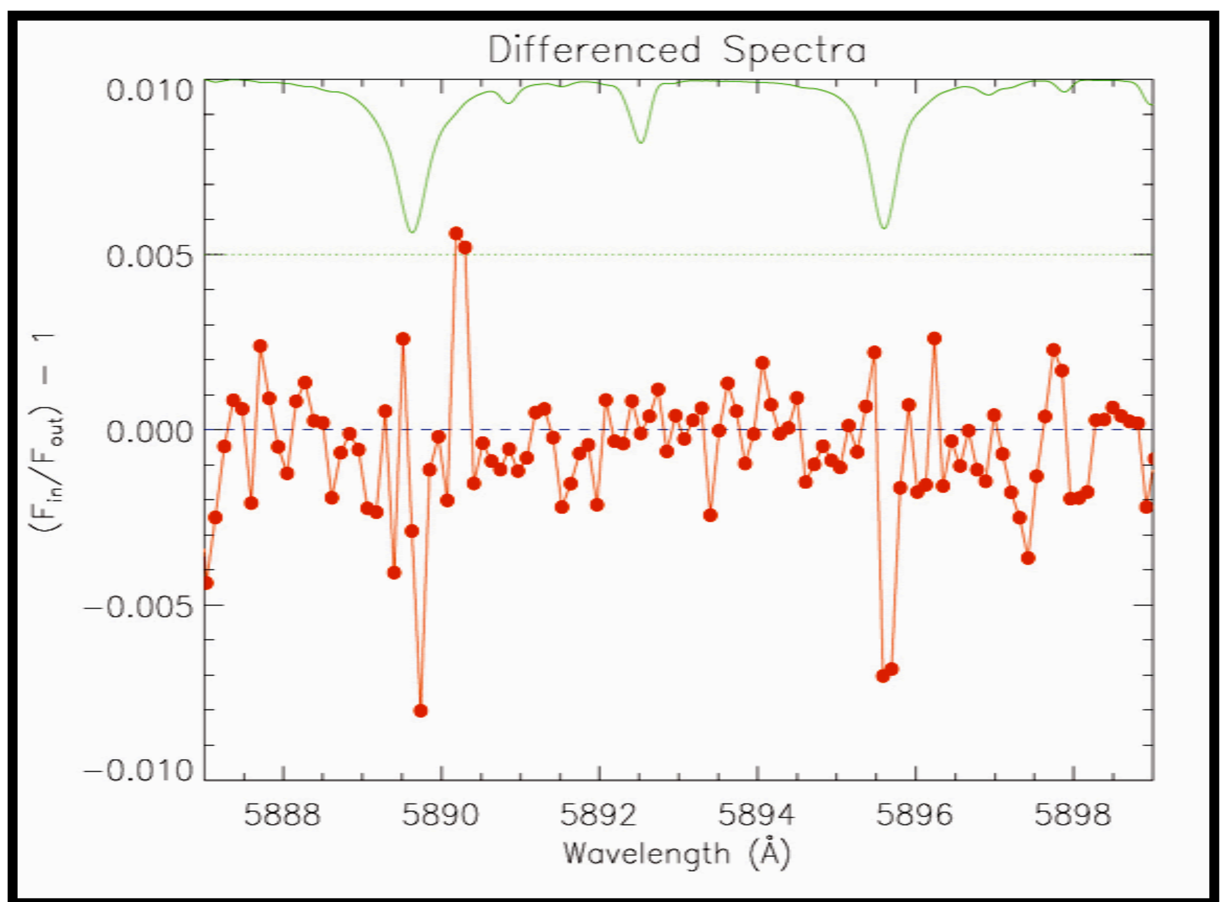
Observations with the Hobby-Eberly Telescope (HET) were used to make the first ground-based detection of a specific element, sodium, in an exoplanetary atmosphere (Redfield et al. 2008). We are now in possession of a rich dataset of similar high-resolution (R~60,000) optical spectra from the HET. Our survey includes multiple in-transit and out-of-transit observations of four different exoplanetary systems with observations under way on a fifth system. This dataset provides very high signal-to-noise coverage of the spectral region from ~5000-9000 angstroms and is a wonderful opportunity for comparative exoplanetology. We will discuss in detail our investigation into these systems, including the data reduction processes and details of the transmission spectrum line analysis. Special attention is paid to the resonant lines of alkali metals (especially Na I and K I) that we expect to see at the temperatures of these exoplanets, which are all hot Jupiters or hot Neptunes. We will also discuss potential long-term prospects of our work, including deriving complete optical atmospheric transmission spectra of these exoplanets and searching for exospheric absorption.

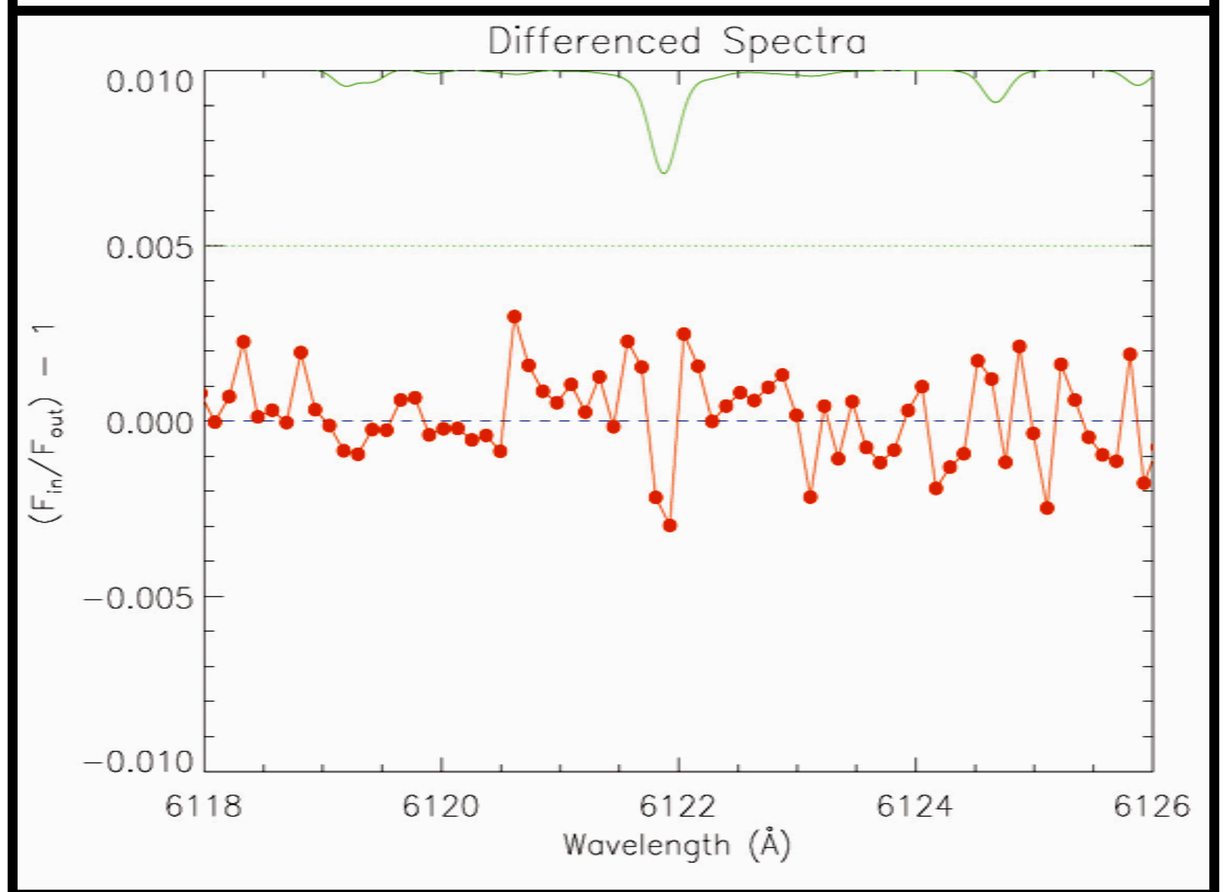
(1) Background

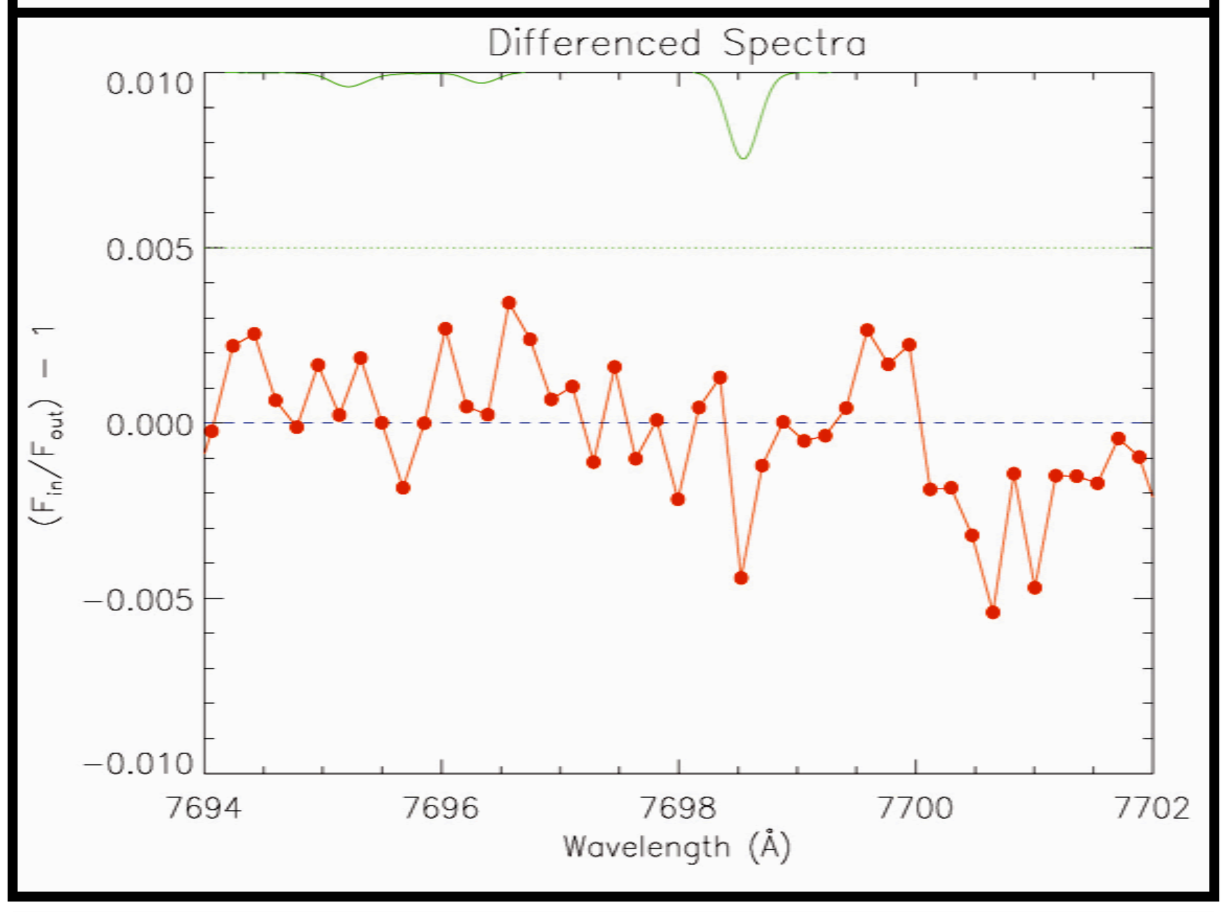
When Charbonneau et al. (2000) presented the first evidence of an extrasolar planet that passed in front of its host star, it opened up a whole new avenue of study—the ability to search for the atmospheres of exoplanets by searching for wavelength-dependent differences in the depth of transits. There have since been several detections of specific atomic or molecular species in exoplanetary atmospheres, mainly in two targets—HD 189733 and HD 209458. These detections include H_2O, CH_4, CO_2, and CO (Grillmair et al. 2008; Swain et al. 2009a,b, 2010).

All of the aforementioned detections used photometric methods. However, two detections of Na I (Charbonneaus et al. 2002; Redfield et al. 2008) used spectroscopy rather than photometry. High-resolution spectroscopy has a significant advantage in that specific atomic or molecular transitions can be identified and their profiles can be analyzed. This is not the case with broadband photometric methods where observed absorption can only be attributed to specific transitions (and their corresponding species) through models.

We have obtained high-resolution (R~60,000) spectra of four exoplanetary systems in an attempt to make further detections of exoplanetary atmospheres. In this poster we describe our ongoing research and preliminary results.





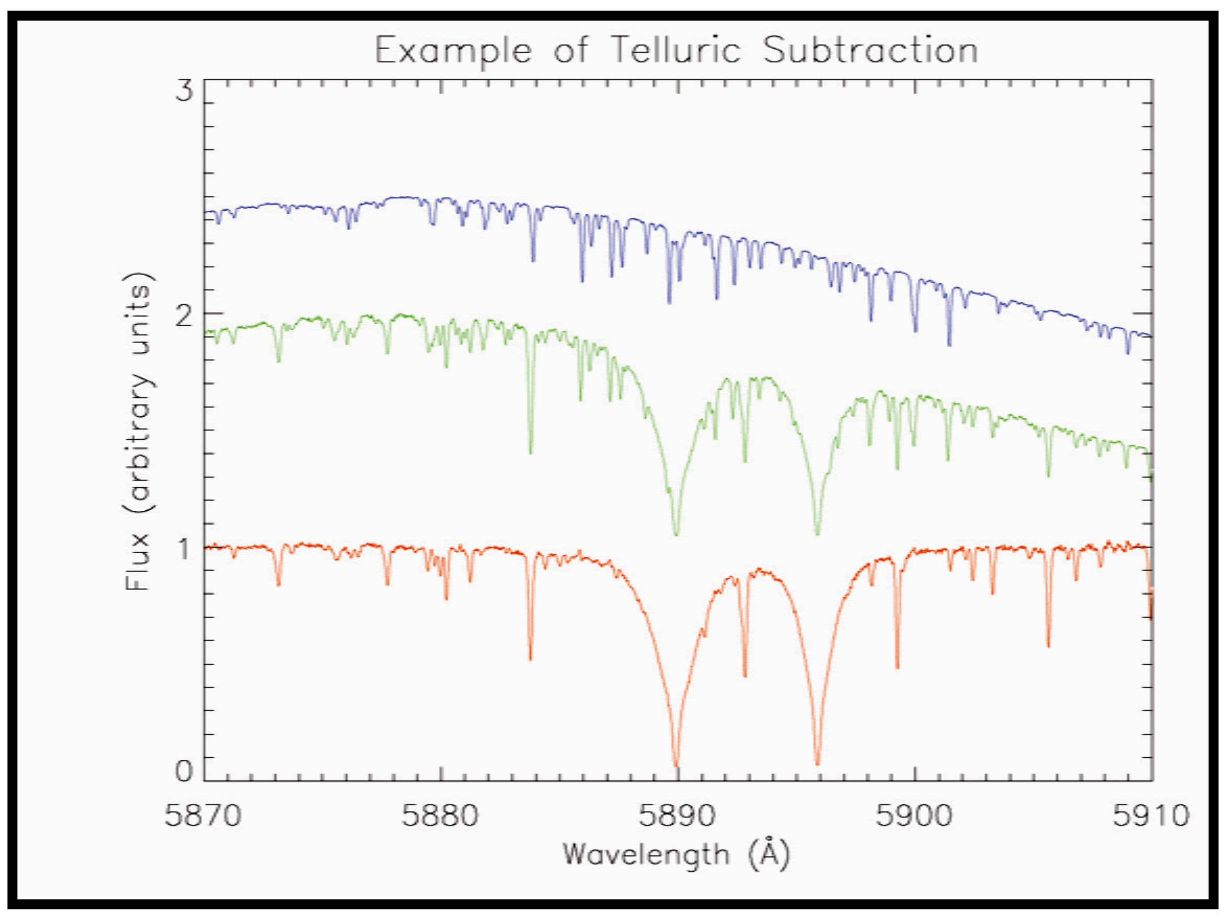


Figures above—the differenced spectra results for HD 149026. Green is the normalized, scaled, coadded out-of-transit spectrum (with dotted reference line) and red is the differenced spectrum (with blue dashed line at 0). ***Top***: The features at Na I are apparent. ***Center***: There is a marginal visual residual at Ca I, but the integration over the profile is zero, and the depth of the residual is comparable to the noise. ***Bottom***: The case for K I is similar to the case for Ca I. In all cases, the full width of the plot corresponds to the region of integration, or the "bandpass" (see Box 3).

(2) Observations

Observations were made with the Hobby-Eberly Telescope's High-Resolution Spectrograph (HRS) at a resolution of R~60,000. For each object, over 100 total exposures of 10 minutes are taken, with over 20 exposures taken while the planet is transiting its host star. Each 10 minute exposure has a S/N of ~100-300, with a few isolated exceptions due to exposures attempted under poor weather conditions. We select custom targets as telluric references. These telluric targets are near in the sky to and observed immediately before or after the primary science targets. The spatial and temporal proximity reduces air mass and water vapor differences; we require telluric target S/N > 1000.

All spectra are extracted using standard IRAF procedures to remove the bias level, flatten the field, remove scattered light, extracted the flux, and set the wavelength calibration from the ThAr exposures. Primary science targets, telluric targets, and ThAr exposures are all extracted.



(3) Methods

Once we have extracted spectra (see Box 2), we perform the following procedures:

- Fit the telluric standard spectra to stellar and ISM models to remove the imprint of broad stellar and weak ISM absorption lines
- Use the IRAF procedure TELLURIC to subtract the telluric spectra from the primary science spectra
- Perform an improved normalization on the telluric-subtracted spectra (the telluric subtraction removes the majority of the blaze function imprint and thus partially normalizes the spectra)
- Calculate errors from photon statistics and read noise, modified by the normalization imprints
- Cross-correlate the spectra and perform a higher-order wavelength correction
- Coadd the spectra
- Cross-correlate and wavelength correct the coadded in transit spectra compared with the coadded out of transit spectra
- Difference and rebin the coadded in and out of transit spectra

With the final differenced spectrum for each object, we perform a final normalization and sum over a several Å bandpass in order to make a measurement of the absorption.

(4) Results

We have four targets that we examine for evidence of Na I (λλ5889,5895), Ca I (λ6122), and K I (λ7698). While we expect Na I and K I to exist in atomic form in hot Jupiter atmospheres (and for these ground-state resonance lines to exhibit absorption), this is not true of Ca I, which functions as a control line.

We tentatively detect Na I absorption in three of our four targets. The remaining target, which has the lowest S/N, shows nominal surplus rather than a deficit, i.e. nominal emission. In all cases we have not performed a complete error analysis of the lines and only have rough estimates of the confidence level.

We do not detect Ca I absorption in any of our targets. Two targets show the smallest abundance deficit, and another two targets show slight abundances that are much smaller than the Na I deficits observed. Because Ca I is our control line, this implies that our detections of Na I are not due to simply a systematic error of differencing strong stellar lines.

We find small deficits for three of the four K I bandpass measurements, implying absorption. However, these are smaller than the deficits we see for Na I, and further refinement is needed to assess the reality of these deficits.

Examples of differenced spectra for HD 149026 are shown at left.

Target	# of In-Transit Observations	# of Out-of-Transit Observations
HD 147506	26	86
HD 149026	23	89
HD 189733	39	172
HD 209458	29	72

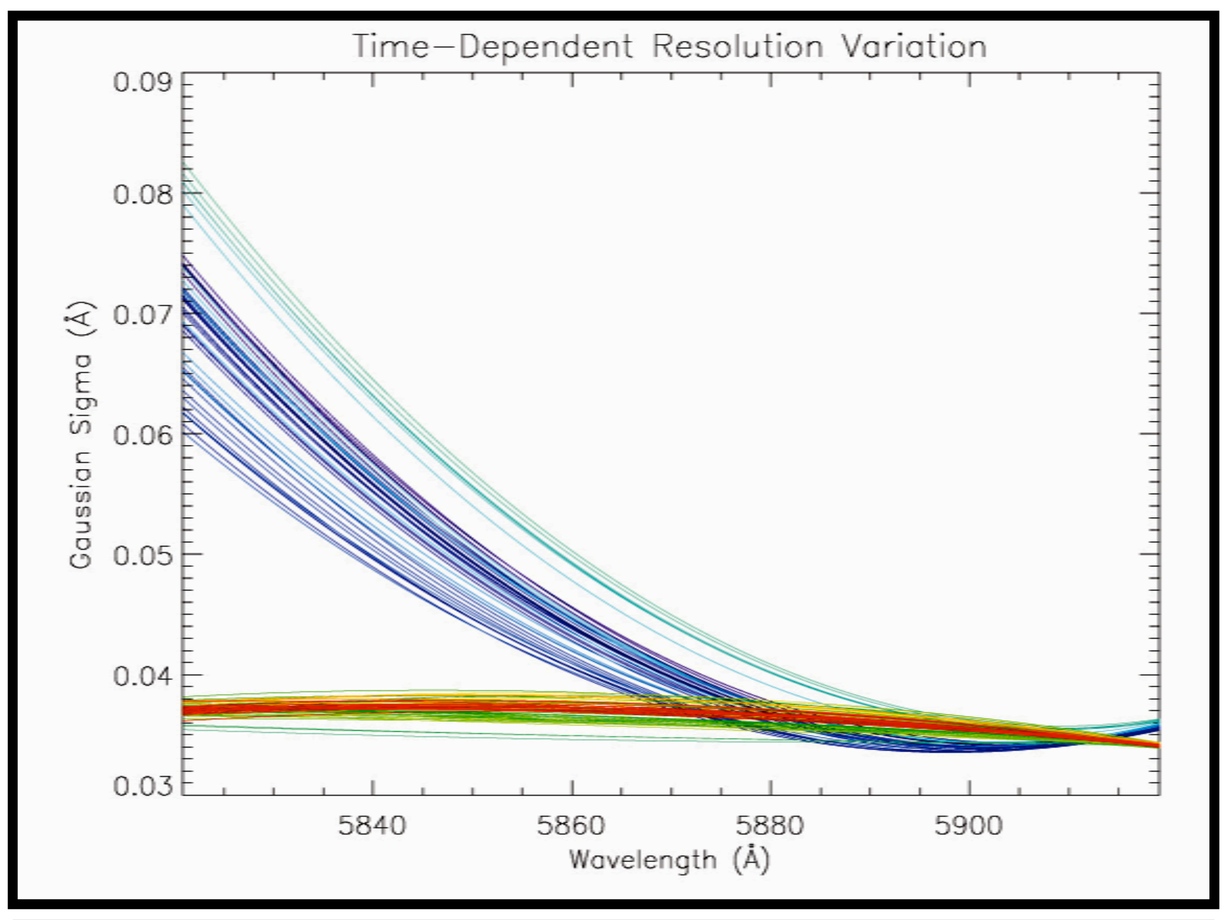
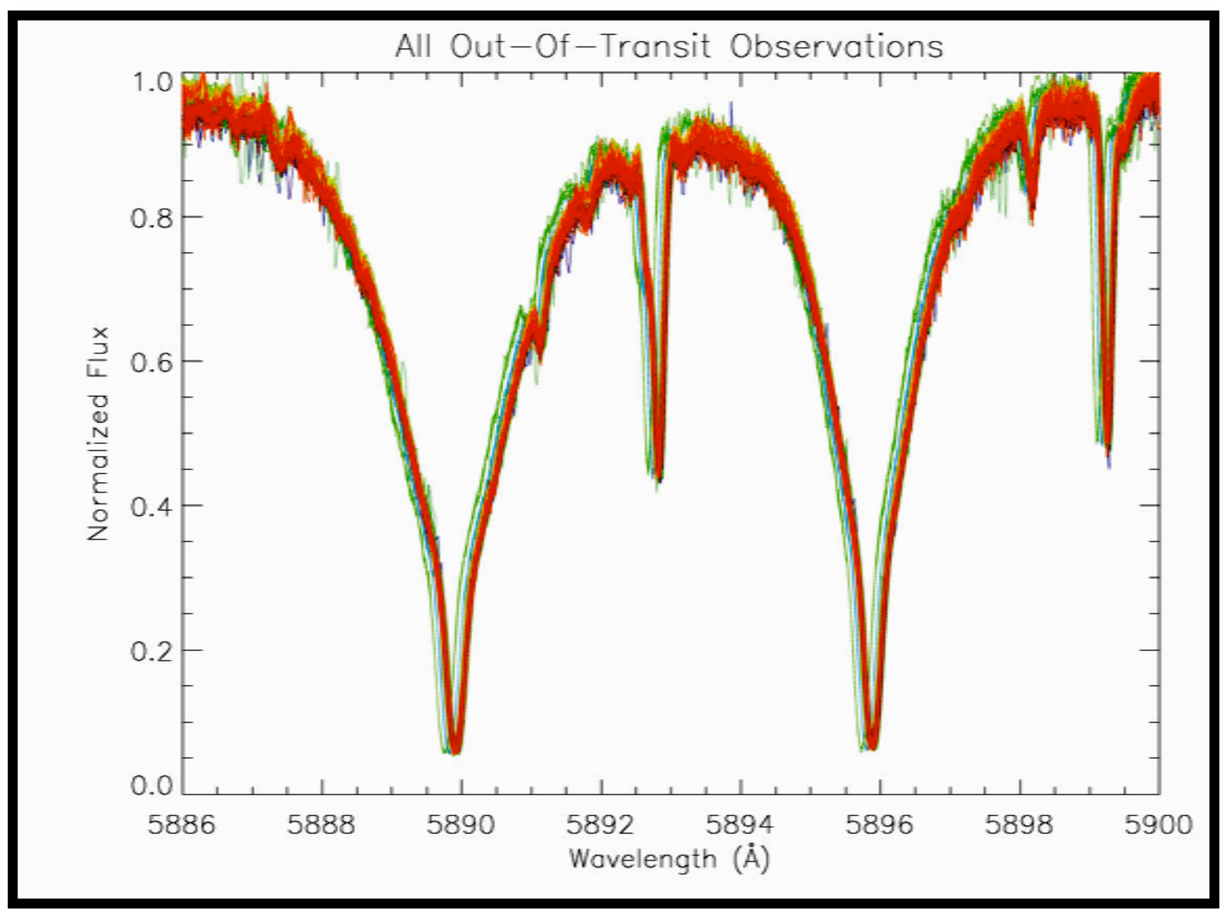


Table at top—a list of our observed targets, with the number of 600s in- and out-of-transit observations. **Figure at left**—example of the telluric subtraction process. Blue—telluric spectrum; green—raw science spectrum; red—science spectrum, telluric-subtracted and normalized. Blue and green spectra are arbitrarily scaled and offset. **Figure above**—an example of one data reduction challenge, instrumental resolution varying in time and with wavelength. The echelle order containing the Na I D doublet is shown. The rainbow of colors corresponds to time, blue is fall 2006 and red is late 2008, with intermediate colors signifying intermediate times. **Figure below**—an example of all of the out-of-transit observations for one of our targets. From here, resolution and wavelength corrections must be applied. Colors as in figure above.



(5) Future Work

The results presented in this poster are preliminary. There are some refinements that remain to be made to our normalization, coadding, and differencing processes. We also intend to more rigorously assess our errors by performing an empirical statistical analysis similar to that performed by Redfield et al. (2008).

Following these refinements, the next step in our program is to perform similar searches for additional resonances lines that are expected in our models. If we are unable to detect additional lines, we will still be able to place upper limits.

Another way in which we intend to expand our work is to use the variety of orbital phases in this rich dataset to look for exospheres or examine secondary eclipses.

Finally, a long-term goal of this program is to fully characterize the transmission spectra of these exoplanets.

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(6) References

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Be sure to visit our companion poster—#2.19 by Seth Redfield et al.