Precise Optical Transmission Spectra for a hot Jupiter & a nearby super-Earth

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ABSTRACT

I propose to use optical transmission spectroscopy from *HST*/STIS to better understand the atmospheric properties of the inflated hot Jupiter WASP-52b and the nearest known transiting super-Earth HD 219134b. In the case of WASP-52b, my analysis will yield information about the presence and composition of clouds in its atmosphere. In the case of HD 219134b, my analysis aims to search for the planet's atmosphere as well as improve its radius measurement to better constrain interior models. Both targets are ideal for transmission spectroscopy, given their bright stellar companions. This work will pave the way for atmospheric analyses of a larger sample of targets from the *HST* Panchromatic Comparative Exoplanetology Treasury (PanCET) program in addition to nearby targets to be discovered by TESS and followed-up by *HST* and JWST.

Subject headings: planets and satellites: atmospheres — planets and satellites:individual: WASP-52b — planets and satellites:individual: HD 219134b

1. Introduction

With about 3,000 [1] exoplanet discoveries from the NASA *Kepler* mission and ground-based radial velocity & transit searches, we have caught a glimpse of the broad diversity of exoplanets that span a range of masses, compositions, and orbital configurations. Exoplanet population studies have thus far been dominated by analyses of transits and radial velocity data (e.g., Batalha 2014; Brown 2001), but their atmospheric parameters (i.e., chemical composition, temperature, the presence & properties of clouds/hazes) are as yet unclear.

Currently, the best technique for studying exoplanetary atmospheres is transmission spectroscopy (Seager & Sasselov 2000; Brown 2001). Using this technique, we have detected planets with large day-night temperature variations (Stevenson et al. 2014), super-Earths with high-altitude clouds (Kreidberg et al. 2014), and hot Jupiters with a continuum of clear to cloudy atmospheres (Sing et al. 2016). The first UV to IR (0.3 - 8.0 μm) transmission spectrum of a hot Jupiter (Pont et al. 2013) found scattering by clouds/hazes dominant in its spectrum and narrow peaks of Na I and K I, which are expected to be prominent features in clear atmospheres (Seager & Sasselov 2000). Prominent H_2O absorption features in the *HST*/WFC3 spectrum of the hot Neptune HAT-P-11b (Fraine et al. 2014), indicative of a clear atmosphere down to ~1 mbar, show that it is possible to measure the chemical abundances of exoplanets (e.g., Luszcz-Cook & de Pater 2013).

With interesting results for a handful of targets, there are still many open questions. Clouds/hazes appear in many of the atmospheres observed so far, but we lack an understanding of their vertical distribution & chemical composition and cannot presently predict in which planets clouds/hazes appear. And while we already have some results from atmospheric studies of Jupiters (Sing et al. 2016), we are still in the very early stages of unveiling the atmospheric properties of smaller (rocky) planets.

My atmospheric analysis of the hot Jupiter

[1] http://exoplanets.org/

WASP-52b will help answer these questions by adding one more target to the growing number of planets with atmospheres studied via transmission spectroscopy. My analysis of the super-Earth HD 219134b will be the first attempt to observe atmospheric features on a small nearby super-Earth, rendering it one of the first targets in the search for a terrestrial planet atmosphere.

2. Technique: Transmission Spectroscopy

I will study the atmospheres of WASP-52b and HD 219134b using transmission spectroscopy (Seager & Sasselov 2000; Brown 2001). With this method, we can constrain the atmospheric structure and chemical composition of a planet's atmosphere by measuring changes in the planet's transit depth as a function of wavelength. The technique of transmission spectroscopy relies on observing an exoplanet as it passes in front of (transits) its host star. During transit, light from the host star passes through the atmosphere of the planet, revealing the presence of different chemicals in the transmission spectrum. At wavelengths where absorption by atoms and molecules takes place, the planet appears larger because the atmosphere is opaque and we observe variations in the apparent radius of the planet at different wavelengths.

Transmission spectra are primarily sensitive to the relative abundances of different absorbing species and the presence of aerosols. Optical observations can constrain the presence and properties of aerosols in the atmospheres of hot, irradiated planets because Rayleigh or Mie scattering produced by clouds causes a steep slope in the optical. This continnum slope can be used to infer cloud composition and to constrain the presence of haze particles and their sizes. Optical observations also feature prominent absorption lines (i.e, Na I, K I, TiO).

3. Targets & Observations

3.1. WASP-52b: An Inflated Hot Jupiter

WASP-52b is a hot Jupiter (T_{eq} = 1300K) with an inflated radius orbiting an active K star (Hébrard et al. 2013). This planet is an ideal target for atmospheric studies via transmission spectroscopy because it has a large scale height (h = 700 km) and a deep transit ($\delta = 0.168$).

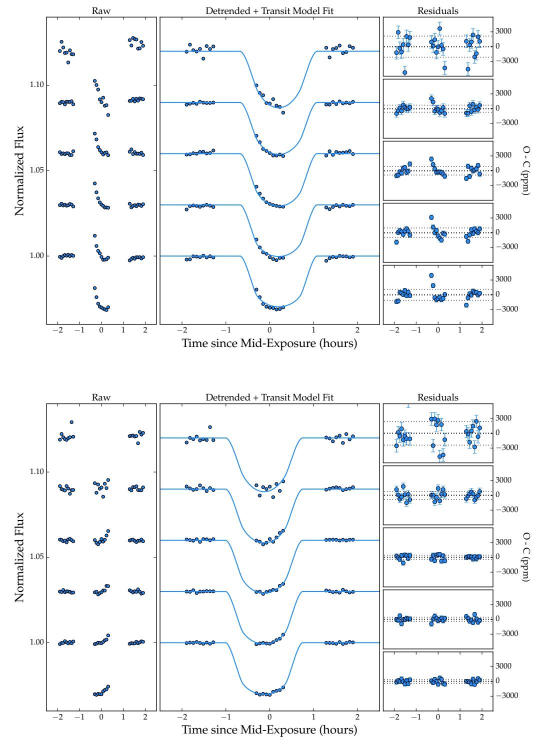

Fig. 1.— *HST*/STIS observations of WASP-52b visits 52 (top) and 53 (bottom). Raw (left panel) and detrended (middle panel) light curves are shown for each wavelength bin, and are offset vertically by an arbitrary constant for clarity. Observed minus computed residuals with error bars are shown in the right panel.

WASP-52b was observed with PanCET[2] in the blue optical (G430L, 2900−5700 Å) on UT 15 Nov 2016 (visit 52) and UT 29 Nov 2016 (visit 53). A third transit observation in the red optical

[2]The Panchromatic Comparative Exoplanetology Treasury (PanCET) Program (PIs: Sing & Lopez-Morales) was awarded 498 orbits on *HST* to observe the atmospheres of 20 giant planets from the UV to near-IR (UVOIR; 0.1 to 1.4 μm) in Cycles 24 and 25. The main scientific goals of PanCET are to: 1) provide a uniform and statistically compelling UV through IR study of clouds/hazes and chemical composition in exoplanet atmospheres; 2) probe planetary mass loss across different environments and in the major three atmospheric chemical species (H, C, and O); and 3) provide a UVOIR legacy sample of transmission spectra of exoplanets that will be well-suited for follow-up with JWST.

(G750L, 5240−10270 Å) is scheduled for mid-May 2017. I will lead the optical atmospheric analysis of this planet, and aim to publish my results by September 2017.

I have begun analyzing these data, and my preliminary results (see Figures 1 & 2) indicate that the transmission spectra are not fully consistent between visits (likely due to stellar activity). Additionally, two recent atmospheric studies of this target claim discrepant conclusions. Louden et al. (2017) cite an optically thick cloud deck to explain its flat transmission spectrum, but note that their results are inconsistent with deeper transit depths at longer wavelengths (Kirk et al. 2016). Conversely, Chen et al. (2017) report a cloudy atmosphere with a noticeable Na I detection (5893 Å) and a weaker detection of K I at 7665 Å.

After extracting a transmission spectrum for the G750L observation (scheduled for mid-May 2017), I will use the full *HST*/STIS optical transmission spectrum to correct for stellar activity in WASP-52b using the methods described in Sing et al. (2011) to determine the wavelength dependence of activity and its effect on transit depth.

The PanCET observations cover the full optical and are free from telluric systematics, so my analysis will serve to settle the score on the cloud condensate properties of WASP-52b. Coupled with the IR and UV atmospheric analysis of this target (to be led by other members of the PanCET collaboration), these broad wavelength transit observations will enable us to fully characterize the atmosphere of this inflated hot Jupiter.

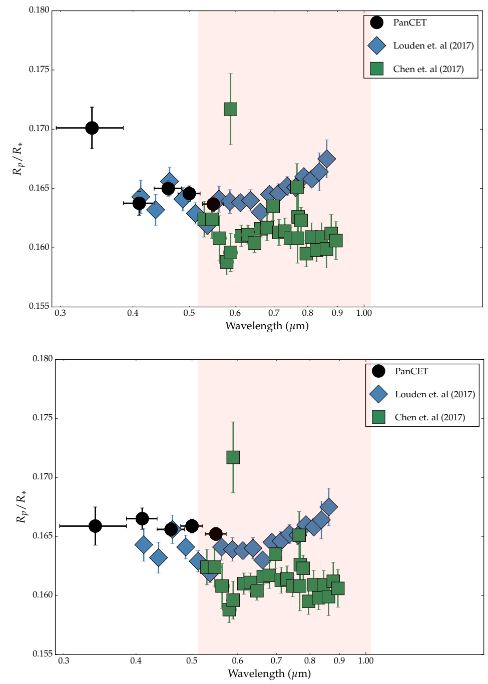

Fig. 2.— Optical transmission spectrum for WASP-52b (black circles), visit 52 (top panel) and visit 53 (bottom panel). For comparison, the published transmission spectra from Chen et al. 2017 (green squares) and Louden et al. 2017 (blue diamonds) are included. The red shaded region indicates the wavelength coverage of the G750L transit data from PanCET to be observed in mid-May 2017.

3.2. HD 219134b: The Nearest Known Transiting Super-Earth

The nearest known transiting super-Earth HD 219134b has a mass of $4.5M_{Earth}$ and radius of $1.6R_{Earth}$, and orbits a bright (V = 5.6 mag) star at a distance of 6.5 parsecs from the Sun. After its discovery by the HARPS-N team using precise radial velocity techniques (Motalebi et al. 2015), follow-up photometric observations with *Spitzer* discovered transits and confirmed this planet's rocky composition.

Models based on chemical equilibrium calculations (Schaefer et al. 2012) predict the gaseous atmosphere of HD 219134b to be CO-dominated with significant amounts of CO_2, and smaller amounts of H_2O and H_2. This atmospheric composition corresponds to a bulk silicate Earth (BSE) rocky composition (Kargel & Lewis 1993), atmospheric temperatures between 1000-2000K, and a 1-bar pressure. Other model scenarios include an atmosphere with low H and C abundances or a H_2O dominated atmosphere.

HD 219134b is thought to be part of the population of highly irradiated dense planets, according to the mass-radius diagram described in Dressing & Charbonneau (2015). Based on interior models from Zeng & Sasselov (2013), these planets have fully differentiated iron cores surrounded by lower density magnesium silicate mantles and are best described by a two-component iron magnesium silicate model.

However, since these models do not incorporate the presence of lighter elements in the core or the inclusion of H_2O in the mantle, they underestimate the absolute core mass fractions. With updated models by Zeng et al. (2016) and smaller errorbars on its radius measurement, we can estimate a more precise planetary radius to better characterize the bulk composition of HD 219134b.

There are currently four STIS observations of this planet available through the public archive of approved *HST* programs[3]. The first three observations were obtained as part of Program 13665 (Exploring the Diversity of Exoplanet Atmospheres in the Super-Earth Regime, PI: Björn Benneke) on UT 04 Nov 2015, 22 Mar 2016, and 10 May 2016. The fourth observation was taken as part of Program 14464 (Atmospheric Sodium and a Precise Radius for the Closest Super-Earth, PI: Mercedes Lopez-Morales) on UT 05 Aug 2016.

My preliminary analysis of the data indicates a transit in the raw light curve, but the signal is muted by systematics related to saturation due to the bright host star (see Figure 3). To extract a precise transmission spectrum for this target, I will first need to modify my existing STIS data reduction pipeline to work with saturated data. My results will produce the first analysis of the atmospheric composition of this planet and improve its radius estimate.

4. Timeline

I aim to complete the proposed analysis described in Sections 3.1 and 3.2 according to the timeline below.

WASP-52b

- May 2017: begin analyzing G750L transit data & extract transmission spectrum
- June 2017: combine all transit data & produce final transmission spectrum (0.4 - 1.0 μm) corrected for stellar activity
- August 2017: model the atmosphere using `ExoTransmit`[4] (Kempton et al. 2017) in collaboration with STSci PanCET members & interpret models/transmission spectrum
- September 2017: submit paper for publication

HD 219134b

- September 2017: optimize my existing pipeline to run on saturated data
- October 2017: combine all transit data & produce final transmission spectrum
- December 2017: model the atmosphere using `ExoTransmit`
- January 2018: interpret models/transmission spectrum
- March 2018: submit paper for publication

[3] `http://www.stsci.edu/hst/scheduling/program_information`

[4] `https://github.com/elizakempton/Exo_Transmit`

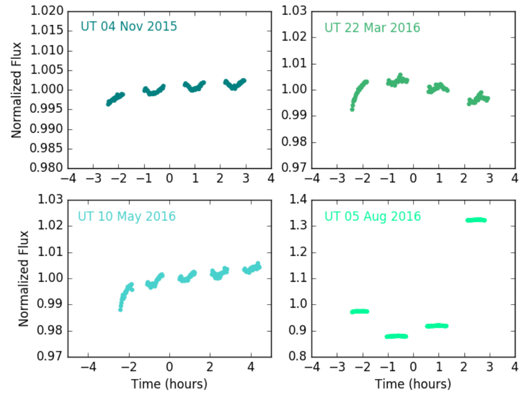

Fig. 3.— Raw light curves for *HST*/STIS observations (grism: G750M) of HD 219134b.

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