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Exoplanet Transit Spectroscopy of Hot Jupiters Using HST/WFC3

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Abstract. We present analysis of transit spectroscopy of three extrasolar planets, WASP-12 b, WASP-17 b, and WASP-19 b, using the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST). Measurement of molecular absorption in the atmospheres of these planets offers the chance to explore several outstanding questions regarding the atmospheric structure and composition of these highly irradiated, Jupiter-mass objects. We analyze the data for a single transit for each planet, using a strategy similar in certain aspects to the techniques used by Berta (2012), and achieve almost photon-limited results for individual spectral bins. Our final transit spectra are consistent with the presence of a broad absorption feature at 1.4 μm most likely due to water, but the amplitude of the absorption is less than expected based on previous observations with *Spitzer*, possibly due to hazes absorbing in the NIR. However, the degeneracy of models with different compositions and temperature structures combined with the low amplitude of any features in the data preclude our ability to place unambiguous constraints on the atmospheric composition without a comprehensive multi-wavelength analysis.

Keywords. stars: planetary systems, transits, techniques: photometric, techniques: spectroscopic

1. Introduction

The Wide Field Camera 3 (WFC3) on the *Hubble Space Telescope* (HST) provides the capability for spectroscopic characterization of molecular features in exoplanet atmospheres. WFC3 is an optical/NIR camera with the capability for slitless grism spectroscopy, with wavelength coverage in the the IR spanning between 0.8 and 1.7 μm (Dressel (2012)). This region spans both the major bands of water between 1.3 and 1.5 μm as well as another water band at 1.15 μm, and bands of a few other molecular species. Observations measuring flux within NIR water bands are impossible from the ground due to the extinction and variability caused by water vapor in the Earth's atmosphere; WFC3 therefore represents the only current platform for measuring absorption and/or emission from water in exoplanet atmospheres.

We present WFC3 observations of three transiting "hot Jupiter" exoplanets - WASP-12 b, WASP-17 b, and WASP-19 b - during transit of the host star. Two of these data sets, WASP-17 b and WASP-19 b, were observed as part of a large HST program to examine single transits and eclipses from a number of hot Jupiters (P.I. D. Deming), while the

Table 1. Observing details for all three targets. Note that larger subarray size and higher peak pixel values correspond to larger peak to peak systematics.

	WASP-12	WASP-17	WASP-19
Date of Observation	2011-04-12	2011-07-08	2011-07-01
Integration Time (seconds)	7.624	12.795	21.657
Subarray Mode (pix^2)	256	512	128
CALWF3 version	2.7	2.3	2.3
NSamp	3	16	5
Timing Sequence	SPARS10	RAPID	SPARS10
Peak Pixel Value (counts)	38,000	64,000	73,000
Peak to Peak Systematics Range (Combined Light) (10^{-3} Normalized Flux)	0.80	3.94	1.62

data for the transit of WASP-12 b were taken as part of a single-object campaign (P.I. M. Swain) and first analyzed in Swain *et al.* (2013). Observational details are listed in Table 1. All three planets orbit extremely close to their parent star, are therefore highly irradiated, and have large atmospheric scale heights, making them excellent targets for transmission spectroscopy.

Recent observational studies have produced conflicting results regarding the atmospheric compositions of several hot Jupiters, including WASP-12 b and WASP-19 b. Madhusudhan *et al.* (2011) first raised the possibility of a non-solar abundance in the atmosphere of WASP-12 b using occultation measurements in four *Spitzer* photometric bands (Campo *et al.* 2011) and three ground-based NIR photometric bands Croll *et al.* (2011) to constrain the carbon-to-oxygen ratio to super-solar values, possibly greater than unity. Similar *Spitzer* and ground-based measurements for WASP-19 b were consistent with both solar and super-solar C/O models (Anderson *et al.* 2011), raising the possibility of a population of carbon-rich hot Jupiters. However, Crossfield *et al.* (2012) recently re-analyzed the *Spitzer* data for WASP-12 b in light of the discovery of a faint candidate companion imaged by Bergfors *et al.* (2012), concluding that the dilution-corrected *Spitzer* and ground-based photometry can be fit by solar-metallicity models with almost isothermal temperature structures.

2. Data Reduction and Analysis

WFC3 data show strong systematics, first described by Berta *et al.* (2012). Swain *et al.* (2013) examines the systematics from multiple observing campaigns, and determines that the systematics are mainly influenced by the maximum exposure levels and choice of subarray size. In order to remove these systematics, we employ the divide-oot method described by Berta *et al.* (2012), averaging the out-of-transit, combined-light data to create a template for the systematics, the scaling of which we leave as an open parameter when fitting our channel light curves (see Figure 1). For fitting purposes, we use a Markov Chain Monte Carlo (MCMC) routine with a Metropolis-Hastings sampler Ford (2005), using the light curve model from Mandel & Agol (2002), with additional terms to account for the gradual decrease in flux seen in all WFC3 exoplanet transit data to date, the systematics scaling term, as well as two further scaling terms to account for shifts on the

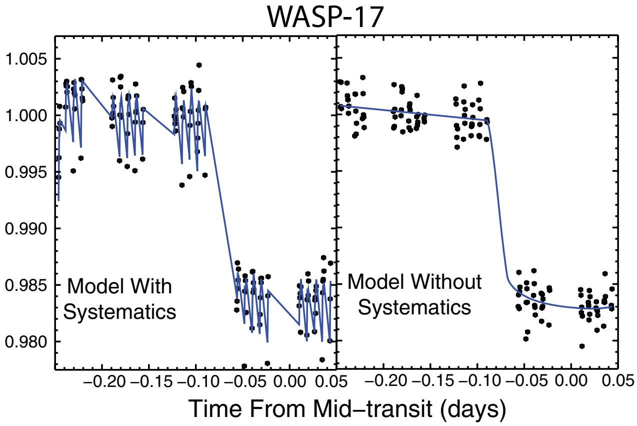

Figure 1. Sample bin for WASP-17 showing the data (black) with model (blue) including systematics (left), and with systematics removed (right).

detector in position and wavelength space. Systematics scaling terms are allowed to vary only if the resulting fit has a $\Delta\mathrm{BIC} \geqslant 2$,

We also take care to remove contamination due to WASP-12's recently discovered companion, Bergfors-6 (Bergfors *et al.* 2012). We do this by using WASP-19's PSF as a template for an uncontaminated source. We determine the positions of WASP-12 and Bergfors-6 in the direct image, place one PSF at the location of each source, and then jointly scale the heights of each using a χ^2 fitting routine.

3. Results

In Figure 2 we show the resulting spectra for each planet and overplot several models based on the framework of Burrows *et al.* (2000) (and more recently Burrows *et al.* (2006), Burrows *et al.* (2008) and Howe & Burrows (2012) and Madhusudhan & Seager (2009) and Madhusudhan *et al.* (2011). The Burrows models calculate the chemical and radiative equilibrium state of each planet based on the mass, size, and incident radiation, assuming solar abundances. For WASP-17, the data is well fit by either a standard model or a hazy, isothermal model, while the data for WASP-12 b is consistent within uncertainties with a flat spectrum.

The Madhusudhan models relax the stringent requirements for radiative and chemical equilibrium, instead exploring oxygen-rich or a carbon-rich chemistry at a specific temperatures (see Madhusudhan 2012 for details). For WASP-19 b the carbon-rich models fit the data slightly better, but we are unable to discriminate between the models based solely on this data.

Huitson *et al.* (2013) have also analyzed the same WASP-19 b data set, and find similar results to our data. Swain *et al.* (2013) and Stevenson *et al.* (2013) have both analyzed the WASP-12 b data, and find a deeper transit depth at the short wavelength edge of the spectrum.

We conclude that the data can be fit with standard atmospheric models, without the need for exotic chemistry or temperature structure. Models with a deep absorption feature are ruled out by our data. However, any of these models can still be adjusted to fit the data by adding an absorbing haze layer or decreasing the water abundance. A determination of the carbon-to-oxygen ratio cannot be deduced from our current data set alone because the location of absorption bands are similar in both oxygen-rich and

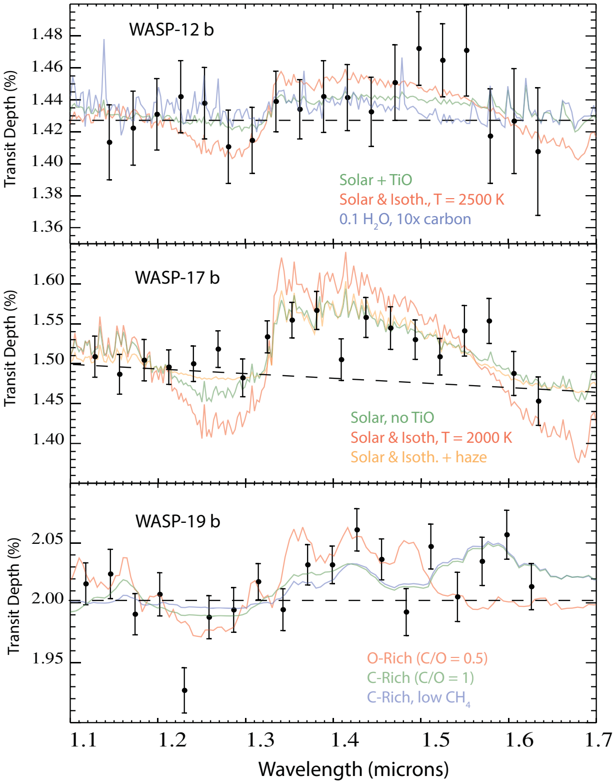

Figure 2. Transit depths for 19 bins for each target, with models from Burrows *et al.* (WASP-17 b and WASP-12 b) and Madhusudhan *et al.* (WASP-19 b). Models show suppressed water features, possibly indicating a haze layer. Data is undergoing further analysis.

carbon-rich models. Similarly, confirmation of the presence or absence of haze requires an analysis of transit depth measurements taken across a wide wavelength range in both the optical and IR, and is beyond the scope of the current work.

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Discussion

TRIAUD: You mentioned that an offset between your results for WASP-12 and Swain's could be due to orbital uncertainties. Which parameters and what precision do you require as it might affect results in other parts, like Rayleigh scattering?

HAYNES: Many parameters can affect this. It is uncertain which are the most important but limb darkening is probably one. Maybe this should be taken more seriously but people have done mostly differential studies rather than absolute.

BARSTOW: Have you considered modeling the WFC3 systematics for removal?

HAYNES: This was one of our first approaches, but considering the short cadence of some of the systematics (only 5 exposures, in the case of WASP-17's hook/ramp effect), and the range of variables that affect the systematics (exposure time, total pixel illumination, sub-array size), we found the divide-oot method to produce much more reliable results.

BARSTOW: Could the high C/O ratio for WASP-19 b also be explained by clouds or haze?

HAYNES: A haze layer or clouds remains a possibility, and there is no way to determine, from the available data, whether we see shallow water absorption features because there is truly little water, or because such features are obscured by haze. This is similar to the case of GJ1214 in Berta *et al.* (2012).