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Probing the extreme planetary atmosphere of WASP-12b

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ABSTRACT

We report near-infrared measurements of the terminator region transmission spectrum and dayside emission spectrum of the exoplanet WASP-12b obtained using the HST WFC3 instrument. The disk-average dayside brightness temperature averages about 2900 K, peaking to 3200 K around 1.46 μm. We modeled a range of atmospheric cases for both the emission and transmission spectrum and confirm the recent finding by Crossfield et al. (Crossfield, I., Barman, T., Hansen, B., Tanaka, I., Kodama, T. [2012b]. arXiv: 1210.4836C) that there is no evidence for C/O > 1 in the atmosphere of WASP-12b. Assuming a physically plausible atmosphere, we find evidence that the presence of a number of molecules is consistent with the data, but the justification for inclusion of these opacity sources based on the Bayesian Information Criterion (BIC) is marginal. We also find the near-infrared primary eclipse light curve is consistent with small amounts of prolate distortion. As part of the calibration effort for these data, we conducted a detailed study of instrument systematics using 65 orbits of WFC3-IR grims observations. The instrument systematics are dominated by detector-related affects, which vary significantly depending on the detector readout mode. The 256 × 256 subarray observations of WASP-12 produced spectral measurements within 15% of the photon-noise limit using a simple calibration approach. Residual systematics are estimated to be ⩽70 ppm.

1. Introduction

Among the more than 700 currently confirmed exoplanets, WASP-12b stands out as exceptional. This transiting gas giant, with a mass of 1.39 MJ and a radius of 1.83 RJ, orbits a 6300-K G star with a period of 1.09 days, resulting in an extraordinary level of insolation and, thus, extreme atmospheric heating (Hebb et al., 2009). Given the close proximity to the stellar primary, this system presents an opportunity to study a planetary atmosphere in a unique environment. The combination of the unusual nature of this system, the relatively bright stellar primary, and the system orientation, which provides both primary and secondary eclipse events, has made this target one of the more extensively observed exoplanet systems. Analysis of these observations has led to several noteworthy results that underscore the unique nature of this planet. For example, WASP-12b is inflated to an unusual degree that could imply significant internal heating (Ibgui et al., 2010). The atmosphere is likely extended, and the planet may be losing substantial mass through Roche lobe overflow (Li et al., 2010); there is also evidence supporting the presence of a magnetospheric bow shock (Llama et al., 2011). The planet has been proposed to be carbon rich, with a C/O ⩾ 1 (Madhusudhan et al., 2011a), a condition that may reduce TiO and VO abundances (Madhusudhan et al., 2011b). Recently, Spitzer measurements were reported that show a large-amplitude thermal phase curve with a significant phase offset at 3.6 μm (Cowan et al., 2012).

High-precision, near-infrared spectroscopy has the potential to provide additional constraints that complement the exiting measurements of WASP-12b. Previous near-infrared spectroscopic observations with Hubble Space Telescope (HST) have detected molecules such as H_2O, CO_2, CH_4, and CO in three hot-jovian-type planets (Swain et al., 2008, 2009a, 2009b; Tinetti et al., 2010) and produced important constraints on the atmosphere of a hot-Neptune (Pont et al., 2009) and Super Earth (Berta et al., 2012). The need for near-infrared measurements of WASP-12b has been partially addressed with ground-based photometry (Croll et al., 2011; Zhao et al., 2012) and spectroscopy (Crossfield et al., 2012a), although the precision of these observations was not

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sufficient to detect molecular features. Here we report high-precision, near-infrared spectroscopy measurements obtained with the HST.

2. Methods: observations and data calibration

2.1. Observations

We observed the WASP-12b system using the WFC3 instrument with the G141 grism, which provides spectral coverage from 1.1 to 1.7 μm with a spectral resolution of $R = 300$ at 1.38 μm. The observations reported here consist of two HST visits, each with five consecutive orbits, timed to measure a primary and secondary eclipse event (see Fig. 1). For both events, the observations track the system light curve from pre-ingress to post-egress to provide a spectrophotometric baseline from which the eclipse depth can be measured. The primary eclipse (transit), when the planet blocks some of the light from the stellar primary, probes the transmission spectrum of the planet's terminator region atmosphere. The secondary eclipse (occultation), when the planet passes behind the stellar primary, probes the emission spectrum of the planet's dayside atmosphere. For these observations, the primary and secondary eclipse measurements were timed to be separated by the minimum possible time feasible with HST with the objective of minimizing any effects due to temporal changes in the exoplanet atmosphere or parent star. After both the primary and secondary eclipse observation sequence, we observed a calibrator star, HD 258439, with two consecutive orbits. Detector-specific configuration information, such as integration time and subarray size, is contained in Table 1. Our choices for the detector readout mode maximized the instrument efficiency and avoided the WFC3 overheads that can reduce significantly the instrument efficiency when observing relatively bright objects, such as transiting exoplanet systems.

The near-infrared spectral signatures of transiting exoplanets, for both transmission and emission measurements, require precision measurements; consequently, the potential impact of instrument systematic errors must be considered. A purpose-built instrument, which would eliminate many of these problems, does not yet exist, and the field has to make the best of the instruments available. This underscores the need for careful investigation and a thorough understanding of instrument characteristics. This is best done by a systematic analysis of a large amount of data so that characteristic instrument behavior patterns can be identified. WFC3 is relatively new and an investigation of the instrument is especially timely.

2.2. WFC3 systematics

Here we report on a detailed investigation of WFC3 instrument systematic errors using a large amount of archival data. Readers primarily interested in the science results can skip to Section 2.3.

To characterize the instrument, we analyzed 65 orbits of archive data covering 10 objects, using the data from individual non-destructive reads to mitigate the complicating factors of the range of target brightness and the fact that some groups appear to have over exposed their targets. We probed the detector system by analysis of both the standard pipeline output and lower level data products (both "_raw" and "_ima" archive file types). We searched for a measurement dependence on the instrument optical state by constructing estimates for focus, spectrum position, and spectrum rotation. The spectral extraction and determination of optical state parameters was performed as described in Swain et al. (2009b). In contrast to NICMOS, in which optical state parameters such as focus and spectral position produced large instrument systematics, we find that the WFC3 instrument optical state changes, while measureable, produce negligible systematic changes in the measured spectroscopic flux density. In this regard, we confirm previous findings (Berta et al., 2012). We attribute this independence of the measured flux density on instrument optical state parameters as likely due to a high level of uniformity in the instrument focal plane array. Thus, small changes in the illumination function do not produce significant changes in the measured

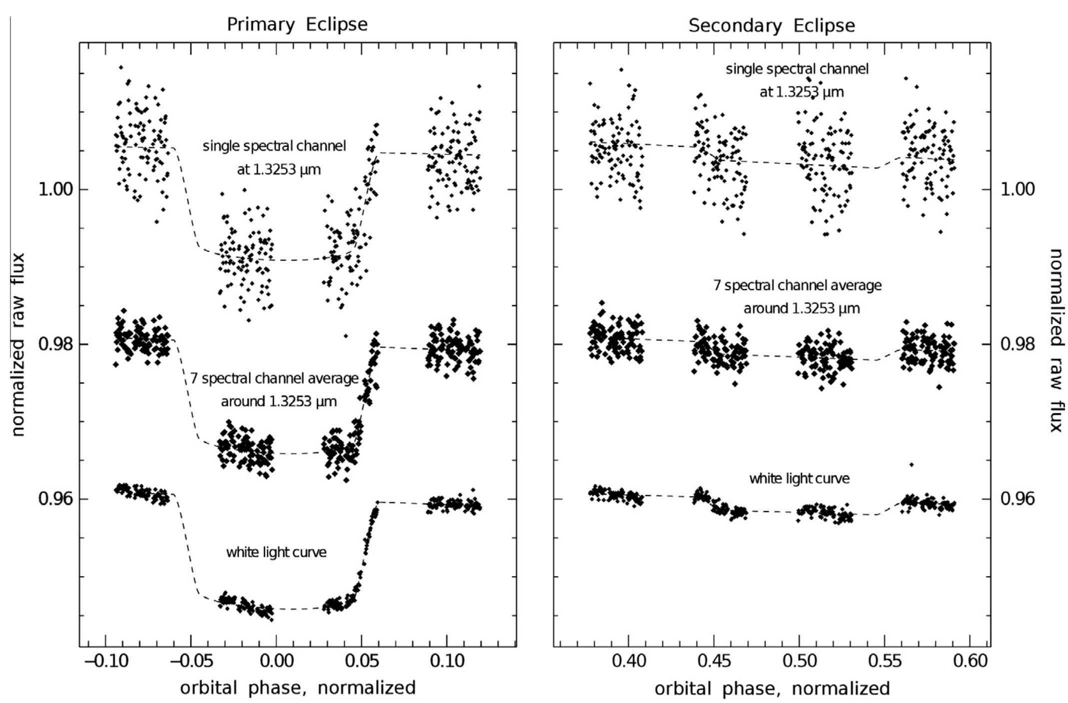

Fig. 1. The WFC3 observation of the WASP-12b primary eclipse (left) and secondary eclipse (right) showing spectral and broad-band light curves as a function of orbital phase. The light curves are based on .flt data (see text for Section 5) for orbits 2–5 and have been vertically offset for display clarity. A best fit linear detrending combined with a light curve model are shown (dashed); no data filtering or decorrelation has been applied. The gaps in the data are due to Earth occultations.