EPJ Web of Conferences **47**, 11003 (2013)
DOI: 10.1051/epjconf/20134711003

Detection of CO in the atmosphere of the hot Jupiter HD 189733b

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Abstract. With time-series spectroscopic observations taken with the Near Infrared Spectrometer (NIRSPEC) at Keck II, we investigated the atmosphere of the close orbiting transiting extrasolar giant planet, HD 189733b. In paticular, we intended to measure the dense absorption line forest around 2.3 micron, which is produced by carbon monoxide (CO). CO is expected to be present in the planetary atmosphere, although no detection of this molecule has been claimed yet. We analyzed the NIRSPEC data with cross-correlation and detect CO absorption in the day-side spectrum of HD 189733b at the known planetary radial velocity semi-amplitude with 99.54% (2.8σ) confidence.

1. INTRODUCTION

One strategy to observe spectral features in the atmospheres of extrasolar planets is by employing intermediate- and high-resolution spectroscopy (i.e. $R = \lambda/\Delta\lambda > 20,000$; λ denotes the wavelength) with very large telescopes. Key to this method is to observe a large number of spectral features in the planet to significanly overcome the planet-to-star flux ratio. In addition, a time-series of spectra is required to observe the planetary features at different orbital phases of the planet, allowing to distinguish between the rather fixed stellar spectrum and the planetary one, which is periodically traveling in wavelength.

In the past, several observing campaigns were carried out at visual wavelengths with the goal to detect starlight reflected from non-transiting hot Jupiters (i.e. massive planets that are a few stellar radii away from their host stars) and to measure their exact masses. Although all those campaigns resulted in a non-detection of reflected starlight, stringent upper limits to the planet-to-star flux ratio and to the geometric albedo of these planets could be, however, established (e.g. Collier Cameron et al. [5], Leigh et al. [10], and Rodler et al. [14]), which provided important constraints to models of the planetary atmospheres.

Very recently, Brogi et al. [3] and our group (Rodler et al. [15]) reported the detection of CO-absorption lines at near-infrared wavelengths in the planetary atmosphere of the hot Jupiter τ Bootis b. Both groups had obtained CRIRES high-resolution spectra around 2.3 micron and retrieved the weak planetary signal from the spectra. As result, Brogi et al. and our group were able to measure the orbital motion of the planet, thereby revealing its orbital inclination and exact mass. Both studies agree with each other (RV semi-amplitude of the planet: $K_\mathrm{p} = 110 \pm 3.2\,\mathrm{km\,s^{-1}}$ and $K_\mathrm{p} = 115 \pm 11\,\mathrm{km\,s^{-1}}$;

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orbital inclination: $i = 44.5 \pm 1.5$ and $i = 46^{+7}_{-6}$ degrees; planet mass: $m_p = 5.95 \pm 0.28\,M_{Jup}$ and $m_p = 5.6 \pm 0.7\,M_{Jup}$, respectively for Brogi et al. and Rodler et al.).

In the present work, we present our studies of the search for carbon-monoxide in the day-side spectrum of the atmosphere of the hot Jupiter HD 189733b.

2. REANALYSIS OF THE HD 189733B-NIRSPEC DATA SET

2.1 HD 189733b

The transiting hot Jupiter HD 189733b is among the best studied exoplanets so far. Discovered in 2005 by Bouchy et al. [2], it has quickly become the favorite target for planet atmosphere studies, being located in one of the brightest known transiting system. Key results include the detection of a hot spot on the planet surface (Knutson et al. [8]) by studying the phase function of the planet in the infrared, indicating a temperature around 1300 K, as well as the discovery of high-altitude haze (Pont et al. [12]; Sing et al. [16]). Several atoms and molecules in the planet atmosphere were found: water (Grillmair et al. [7]), sodium seen in absorption at visual wavelengths (Redfield et al. [13]), as well as methane and carbon dioxide (e.g. Swain et al. [17]; Désert et al. [6]). In addition, Désert et al. [6] found strong absorption around 4.5 μm, probably due to CO. Lecavelier des Etangs et al. [9] measured strong evaporation of the planetary atmosphere due to the high irradiation from the host star.

2.2 NIRSPEC data and their reanalysis

We reanalyzed the data set published in Barnes et al. [1], which had been taken with the goal to detect H_2O and CO in the atmosphere of HD 189733b. Their data analysis, however, resulted in a detection of marginal significance of these elements in the planetary atmosphere. Data were obtained with NIRSPEC (McLean et al. [11]) at the Keck II Telescope, Hawaii, USA, on UT 2008 June 15 and June 22, when the dayside of the planet was almost entirely visible. A total of 373 spectra were recorded using a 1024×1024 InSb Aladdin-3 array, of which 269 were later used in the data analysis. The spectra were taken with a slit width of 0.432 arcsec, giving a spectral resolution of $R \approx 25,000$.

Using the method outlined in Barnes et al. [1] and references therein, we reduced the data and attempted to extract the planetary signature from time-series spectra by removing the dominant spectral contributions: namely the stellar spectrum and the telluric lines. Since we searched for the dense CO absorption forest of the companion spectrum around 2.3 μm, we restricted the data analysis to the last two spectral orders comprising the wavelength region of $\lambda = 2.275$ to 2.31 μm and $\lambda = 2.347$ to 2.383 μm, respectively. In this wavelength regime, Waldmann et al. [18] reported a planet-to-star flux ratio of $\epsilon = 2.2 \times 10^{-3} \approx 1/450$ from secondary eclipse measurements of HD 189733b.

To search for the CO absorption in the day-side spectrum of HD 189733b, we cross-correlated the residual spectra with a PHOENIX spectrum of a brown dwarf with a temperature of T=1500 K and with a spectral resolution of $R = 25,000$. In the cross-correlation, we weighed the spectra according to their average SNR level per spectral pixel, and further accounted for both the systemic radial velocity of the star HD 189733 ($\upsilon_{sys} = -2.4\,\mathrm{km\,s^{-1}}$) and the barycentric velocity of the Earth. We then co-aligned and co-added the individual cross-correlation functions in the planet rest-frame, thereby taking into account the orbital phase information of the planet at the barycentric Julian date of the observations.

3. RESULTS AND CONCLUSIONS

As shown in Fig. 1 (upper panel), we find the strongest candidate feature at $K_p = 154\,\mathrm{km\,s^{-1}}$, which is located within the 1σ-error range of the known RV semi-amplitude of HD 189733b being, $K_p = 152.6 \pm 2\,\mathrm{km\,s^{-1}}$. Since the RV semi-amplitude of the planet K_p is known, we restricted the bootstrap

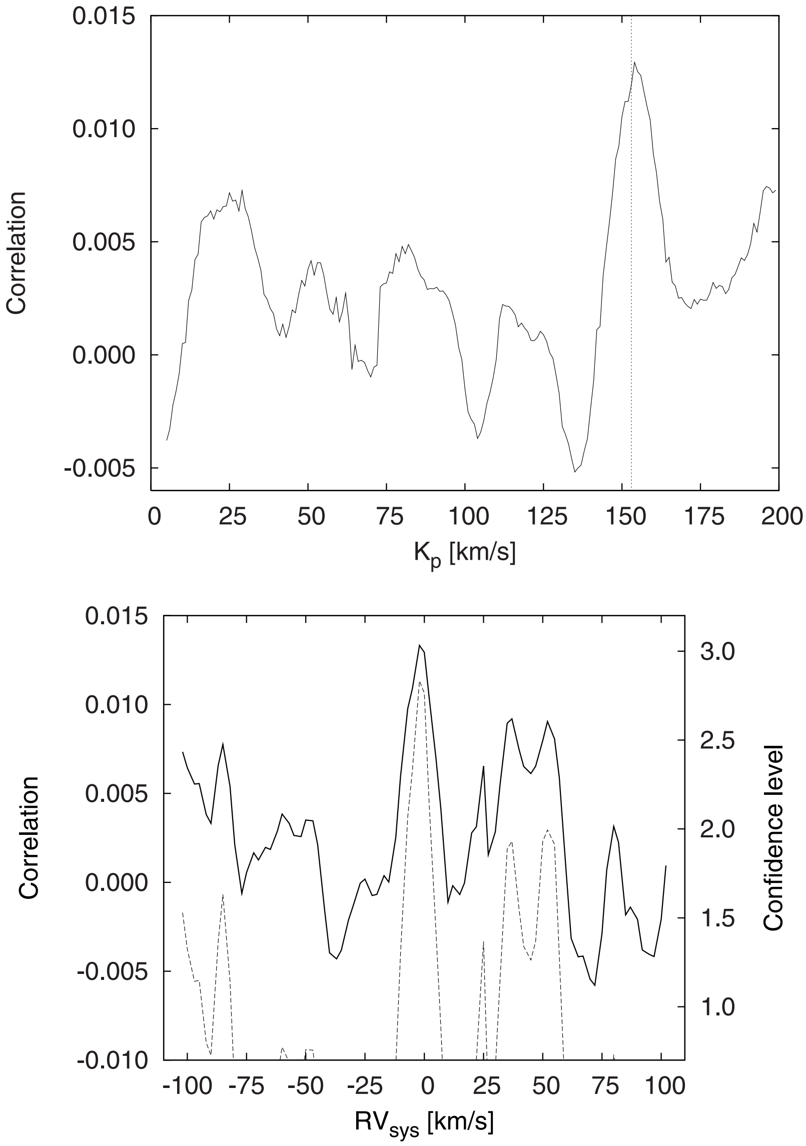

Figure 1. *Upper panel*: Co-added cross-correlation functions in the rest-frame of the planet with respect to the RV semi-amplitude K_p of the planet. The peak of the CCF occurs at *Lower panel*: as a test, we varied the systemic RV of the star HD 189733 and determined the cross-correlation functions (solid line, legend of the y-axis on the left hand side) and the corresponding confidence levels (dashed line, legend of the y-axis on the right hand side) at the measured RV semi-amplitude of the planet, $K_\mathrm{p} = 154\,\mathrm{km\,s^{-1}}$. A clear signal at a 2.8σ-confidence level is visible at the system velocity of HD 189733 ($v_\mathrm{sys} = -2.4\,\mathrm{km\,s^{-1}}$).

randomization run to the search range $K_\mathrm{p} = 152.6 \pm 3\sigma\,\mathrm{km\,s^{-1}}$ (i.e. 146.6 to $158.6\,\mathrm{km\,s^{-1}}$). As a result, we find that the candidate feature is at a confidence level of 99.54% (2.8σ).

We furthermore independently analyzed each of the nights and found that the candidate feature is present in both nights. In an additional plausibility test, we varied the systemic RV of the star HD 189733 and determined the cross-correlation functions at the measured RV semi-amplitude of the planet being $K_\mathrm{p} = 154\,\mathrm{km\,s^{-1}}$. Figure 1 (lower panel) depicts that the strongest cross correlation peak is found around a systemic velocity of $v_{sys} = -2\,km\,s^{-1}$, which is in agreement with the known systemic velocity of HD 189733, $v_{sys} = -2.4\,km\,s^{-1}$.

When plotting the individual cross-correlation functions of the residual spectra with the CO model spectrum, we do not see the planetary signature. Given the relatively large flux ratio between the dayside of HD 189733b and its host star, we should have been able to measure the trace of the planetary RV signal with high confidence under the assumption of high abundance of CO in the planetary atmosphere. We therefore conclude that the atmosphere of HD 189733b exhibits low abundance of CO. In addition, we observe CO in absorption, which indicates that the atmosphere of HD 189733b lacks a strong thermal inversion layer.

We conclude that this 2.8σ-signal constitutes a detection of CO in the day-side spectrum of the atmosphere of HD 189733b. Our result demonstrates the power of high-resolution spectroscopy at infrared wavelengths to investigate the atmospheres of exoplanets.

JB gratefully acknowledges funding through a University of Hertfordshire Research Fellowship. During this research, FR and JB have received travel support from RoPACS, a Marie Curie Initial Training Network funded by the European Commission's Seventh Framework Programme.

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