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# Probing hot Jupiter atmospheres with ground-based high-resolution spectroscopy

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## Abstract

We present recent results from high-resolution spectroscopy of bright transiting and non-transiting hot Jupiters, including preliminary results for the day-side of HD 209458 b. Using the CRyogenic InfraRed Echelle Spectrograph at the VLT, we have detected unambiguous signals of carbon monoxide in the planetary atmospheres through the use of novel data analysis techniques.

The method has proven successful for both transmission spectroscopy of HD 209458 b [4], day-side spectroscopy of HD 189733 b [3] and day-side spectroscopy of the non-transiting planet Tau Bootis b [1]. Furthermore, the non-transiting planet 51 Pegasi b shows a promising combined signal from CO and H2O [2]. These detections can also provide the absolute planet mass, orbital velocity, inclination, and information about the temperature-pressure profile of the planetary atmosphere.

## 1. Introduction

The efforts to characterise exoplanets have been focused on the atmospheres of transiting hot Jupiters. The primitive atmospheres of these giant planets make them interesting probes for their formation history, and they provide an important testing ground for the development of methods for atmospheric characterisation in general.

Early detections of atmospheric signals all came from space-based observatories such as HST and Spitzer. While the space telescopes have the obvious advantage of a lack of disturbing atmosphere, these broad-band observations contain a level of ambiguity, due to overlap in the molecular signatures. This can be avoided using very large ground-based telescopes with high spectral resolution so that individual molecular absorption lines are resolved. The lines appear with a variable Doppler-shift as the planet orbits around the host star, thus allowing them to be separated from the telluric and stellar lines and providing a direct way of determining the orbital velocity and inclination of the planet.

The method works for both transmission and day-side spectroscopy, with the latter being applicable to both transiting and non-transiting planets. For the first time, characterisation of non-transiting planets has become possible.

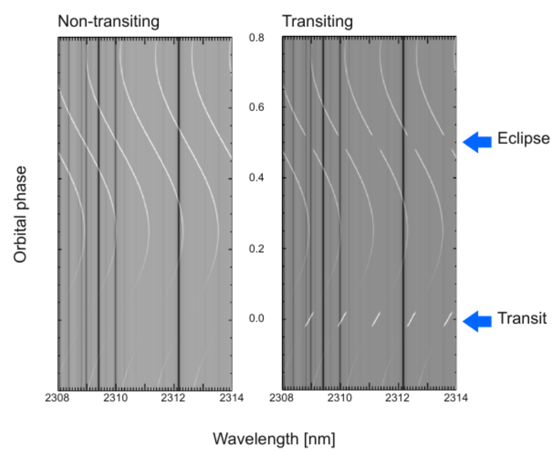


Figure 1: Toy-model of high-resolution ground-based hot Jupiter spectra as a function of orbital phase. The dark vertical bands are telluric absorption. The planet CO signal is shown in emission for clarity. The Doppler-shift of the planet signal varies with orbital phase, and can be seen in both day-side spectra as well as in transmission spectra in the case of transiting planets.

Here we present carbon monoxide detections in hot Jupiter atmospheres, but the technique can be extended to other molecules.

## 2. The CRIRES Survey

The infrared spectrograph CRIRES at VLT UT1, has a spectral resolution of $R = 100,000$, allowing the telluric and stellar lines to be separated from the planetary CO signal. The targets are bright stars ($K > 6$ mag) hosting highly irradiated hot Jupiters, both transiting and non-transiting. Each target is observed in blocks of 5-6 hours, in order for the planet to have a significant change in radial velocity during the time of observation. We observe in the wavelength range $2.28 < \lambda < 2.35 \mu m$, where there are around 50 CO lines.

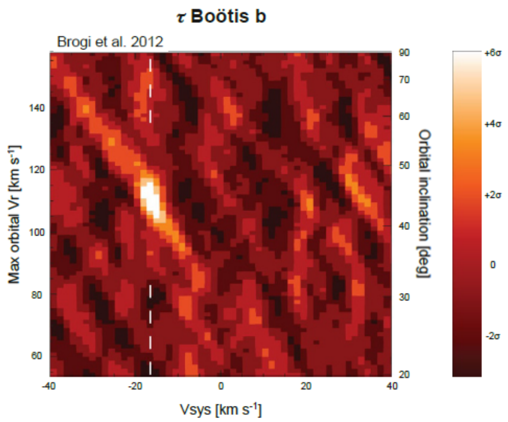


Figure 2: $6.2\sigma$ CO absorption signal in the day-side spectra of $\tau$ Boötis b as function of systemic velocity and the radial velocity amplitude of the planet. The signal coincides with the known systemic velocity (vertical dashed line), and the position of the signal in the parameter space corresponds to a planetary mass of $M_P = 5.95 \pm 0.28 M_{Jup}$. The signal is obtained from cross-correlation between the observed CRIRES spectra and a CO template spectrum, Doppler shifted with a wide range of radial velocities, corresponding to different inclinations of the orbit of the planet.

The airmass corrected spectra are cross-correlated with template spectra with a wide range of Doppler shifts. If the model matches the data, we get a positive (absorption) or negative (emission) signal. Figures 2 and 3, show the total cross-correlation signal from 2-3 nights of observations, summed in time assuming a range of inclinations and a circular orbit.

## 3. Conclusions

Ground-based high-resolution spectroscopy in the near infra-red is a powerful tool for characterising hot Jupiter atmospheres. The orbital motion of the planet is detected and used to separate planetary molecular signatures from telluric and stellar lines.

The detections can be used to constrain abundances as well as temperature-pressure profiles. Furthermore, since we are determining the orbital motion, we can

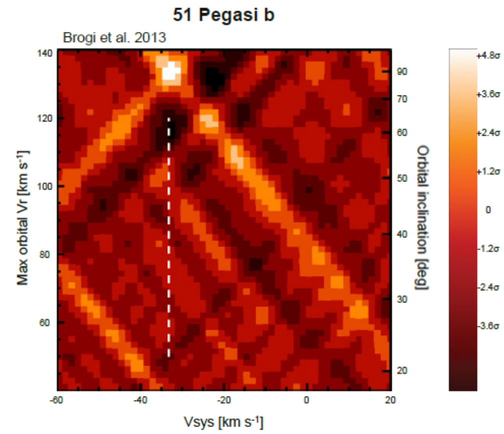


Figure 3: $5.9\sigma$ CO and H2O absorption signal from 2 out of 3 nights of day-side spectra of 51 Peg b. The third night showed no detection, possibly due to a combination of lower data quality and weather. More data are required to confirm or dispute time variability in the atmosphere of 51 Peg b.

also determine the planet-to-star mass ratios, in a manner similar to that of an eclipsing binary system. The method provides the first characterisations of non-transiting exoplanets, and can be extended to other molecules, eg. H20 and CH4 at $3.5 \mu m$.

## References

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