Evidence against a strong thermal inversion in the hot Jupiter HD 209458 b

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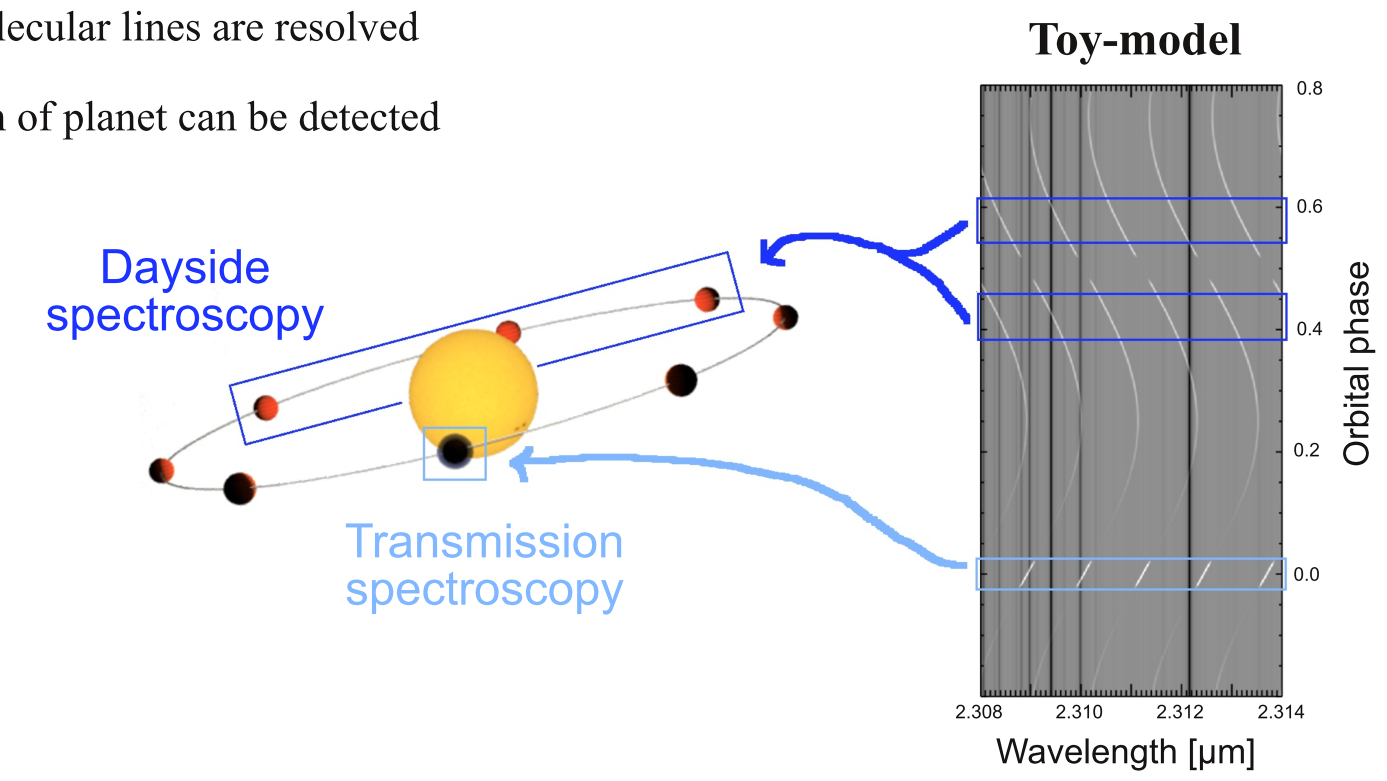
Introduction

Secondary eclipse measurements of several hot Jupiters have indicated the existence of thermal inversions, but their presence is difficult to confirm due to degeneracies between molecular abundances and temperature structure. Furthermore, the causes of presence or absence of inversion layers in hot Jupiter atmospheres are unknown - a question we cannot hope to answer before we can robustly identify inversion layers in exoplanets.

Here we present results from high resolution thermal emssion spectra of the hot Jupiter HD 209458 b, a bright transiting planet that is generally thought to host an inversion layer. Thermal inversions give rise to emission features, so detection of emission lines in the planet spectrum, as opposed to absorption lines, would be direct evidence of the inversion.

The high-resolution method

- CRIRES @ VLT with R ≈ 100,000
- Individual molecular lines are resolved
- Orbital motion of planet can be detected



The above figure show a toy-model of high-resolution ground-based hot Jupiter spectra as function of orbital phase. The dark vertical bands are telluric absorption. Over the course of an observation run (5-6 hours) the Doppler shift of the planet CO lines (in white) changes with tens of km/s, allowing them to be separated from the telluric lines (dark vertical bands).

Individual lines are too weak to be detected, but their signal can be combined by cross-correlating each observed spectrum with a model spectrum. The model is Doppler shifted prior to the cross-correlation over a large range of radial velocities. The resulting cross correlation functions are then shifted to the planetcentric frame and summed in time to provide the total cross-correlation function (T-CCF).

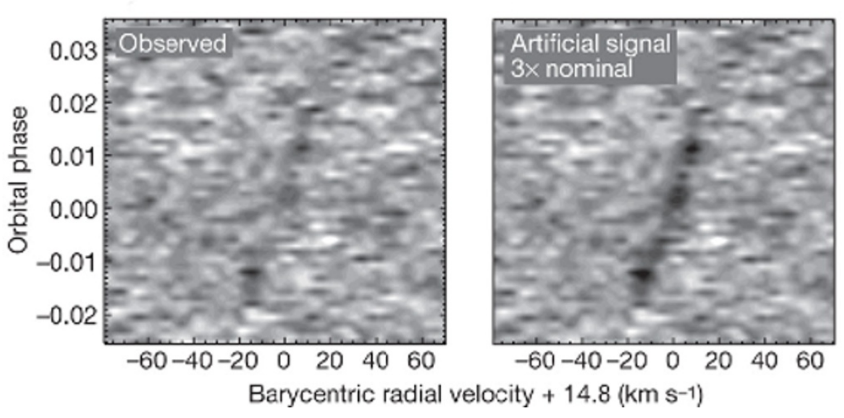
New dayside observations

- 17.5 hours dayside spectroscopi of HD 209458 b with CRIRES VLT
- Targeting CO at 2.3 µm
- Day-side spectra *are* sensitive to the presence of thermal inversions

Earlier CO detection from transit observations

Snellen et al. (2010) observed HD 209458 b during a transit with the high-resolution method. This was the first observation of its kind.

- CO absorption was succesfully detected at 2.3 µm
- Transmission spectra *are not* sensitive to the presence of thermal inversions

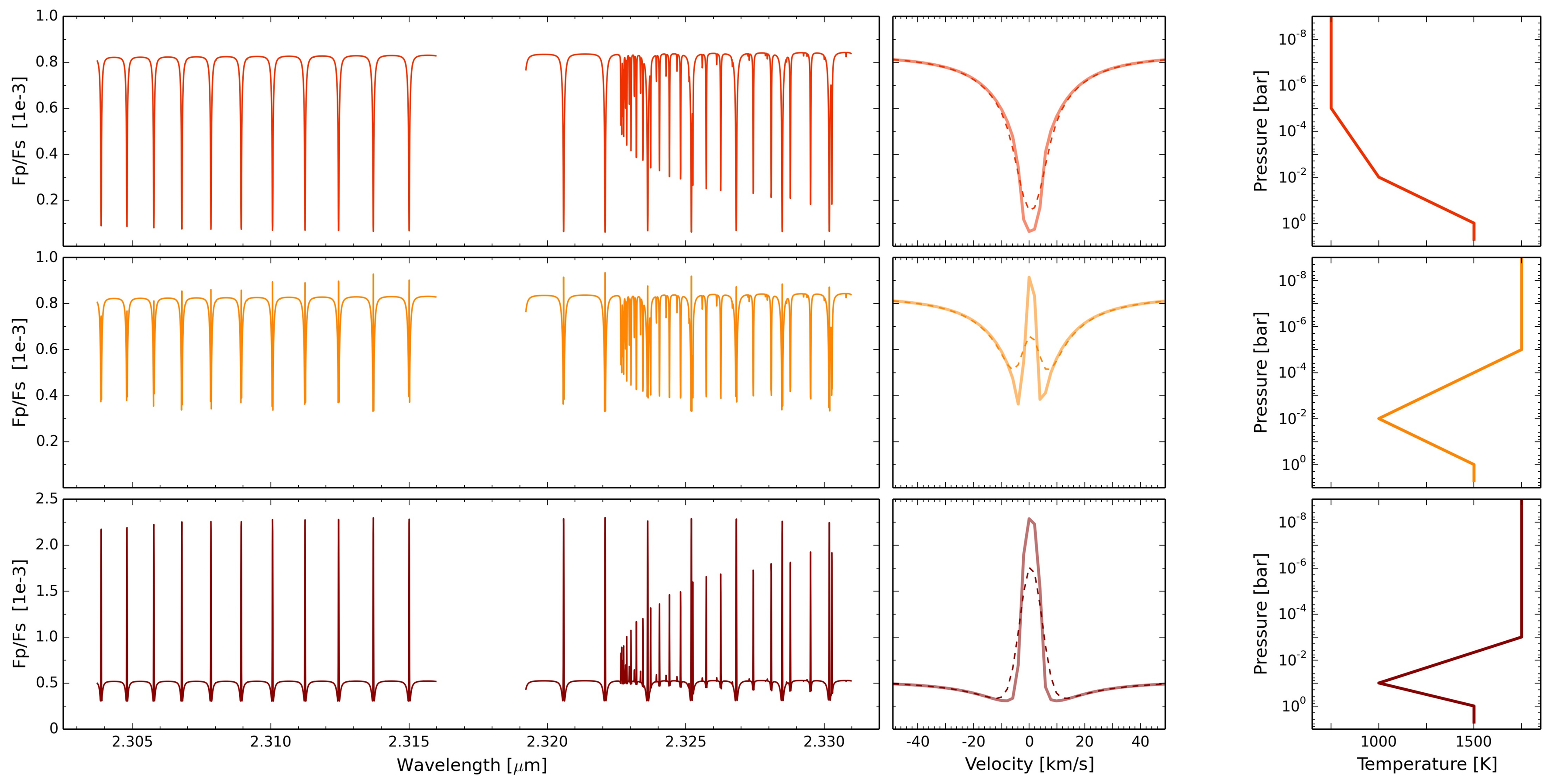


The cross-correlation matrix between a CO absorption model and CRIRES transmission spectra. The planet signal is seen as the tilted darker trail in the left panel. The right panel shows the expected signal at 3x nominal strength.

The models

The model spectra of HD 209458 b were calculated line by line with CO as a single trace gas. Here we show three representative examples from a temperature-pressure grid.

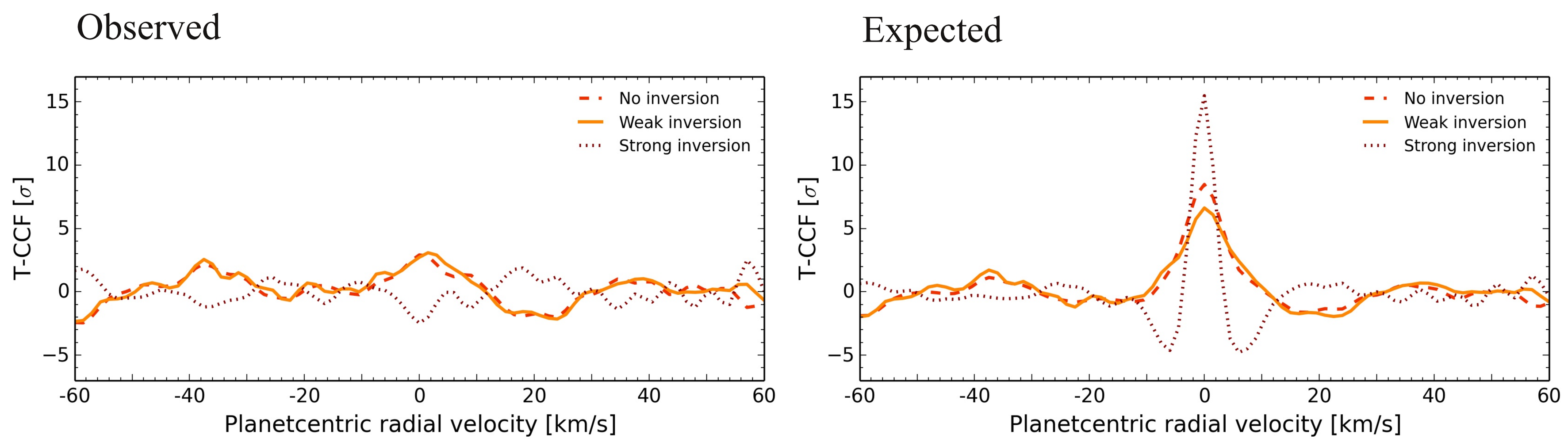
The model without a thermal inversion (top panel) has simple absorption lines, while on the contrary the two models with thermal inversions (middle and bottom panel) show emission at the core of the CO lines and absorption in the wings. The model with the deeper inversion layer (bottom panel) gives the strongest inversion signature in the form of strong emission.



Furthermore, we have cross correlated the observed spectra with template spectra calculated using temperature-pressure profiles similar to those suggested for HD 209458 b in Madhusudhan and Seager 2009. These models have lower altitude inversion layers in the pressure range from 0.5 bar to 0.01 bar and above the inverted layer the temperature again decreases with altitude. This gives rise to strong CO emission lines, but with a little absorption at the core of the lines.

Results from cross correlation analysis

We do not detect any significant absorption or emission of carbon monoxide in the dayside spectrum of HD 209458 b, although cross correlation with template spectra either with CO absorption or with weak emission at the core of the lines show a low significance (2.5 - 3 σ) correlation signal. Models with strong CO emission lines show weak anti-correlation with similar or smaller significance levels. The models with temperature-pressure profiles resembling those of Madhusudhan and Seager 2009 show similar weak anti-correlation.



The left figure shows slices through the total cross correlation functions (T-CCF) from cross correlating the observed dayside spectra with each of the three example models, assuming the literature values for the systemic velocity (Vsys = -14.69 km s^{-1}) and the orbital velocity (Vorb = 140 km s^{-1}).

The right figure shows the expected total cross correlation functions, if the models are correct, based on injecting the model into the observed spectra prior to telluric removal, and cross correlating with the same model.

Discussion & conclusion

High-dispersion spectroscopy has proven successful at detecting molecules from absorption lines for both transmission- and dayside spectroscopy. Given that dayside spectroscopy is sensitive to thermal inversions, it is interesting to see how the technique fares for dayside spectra of HD 209458 b which is believed to have an inversion layer in its upper atmosphere.

We see no convincing evidence for CO absorption or emission, even though CO is known to be present from transmission spectroscopy. In the case of an atmosphere with a thermal inversion, the exact shape of the CO lines and the strength of the emission are strongly dependent on the pressure range covered by the inversion. We have therefore covered a wide range of possible inversion signatures that are detectable with the high-resolution technique. The absence of a CO signal signifies that either the temperature-pressure profile of HD 209458 b is close to isothermal, or the CO signal is heavily muted, possibly due to hazes or clouds.

Collaborators

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Further information

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A pdf version of the poster can be found on www.strw.leidenuniv.nl/~schwarz/TOE2014_poster.pdf