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Revealing Thermospheres of Ultra Hot Jupiters from High Resolution Spectroscopy

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Abstract

We highlight the use of neutral sodium for the characterisation of thermospheres of ultra Hot Jupiters via the examples of HD 189733b and WASP-76b. We discuss the detection of sodium in WASP-76b with the ground-based spectrograph HARPS and the application of nested sampling retrieval to distinguish between different atmospheric models for thermospheres and below.

Introduction

Exoplanetary research is now fully in the stage of atmospheric characterisation. One technique to achieve this goal is transit spectroscopy, where the light of the host star is used during the planet transit to extract the spectrum of the planet atmosphere. To study the upper atmosphere, neutral sodium with its resonant doublet at 589 nm proves especially useful due to its strong signature even for small amounts of sodium in the atmosphere. Aside from detecting atmospheres via the confirmation of sodium, one can also characterise their properties. Given its high cross section, the sodium doublet probes the atmosphere to high altitudes, constraining temperature pressure profiles [1, 2, 3] and dynamical processes up to the thermosphere [4, 5]. Application of this technique to HD 189733b [5, 6] successfully provided a benchmark result, motivating the Hot Exoplanet Atmosphere Resolved with Transit Spectroscopy survey (HEARTS, PI: D. Ehrenreich) that aims at observing gas giants with different masses and irradiation with HARPS. This survey led to the first detection of neutral sodium in an ultra Hot Jupiter [7], WASP-76b, which allows us to unveil the upper atmosphere properties of the planet.

Detecting Sodium in Ultra Hot Jupiters

We detected sodium (10.75 σ) in the ultra Hot Jupiter WASP-76b [7] with the HARPS spectrograph over three transits. High resolution spectroscopy with ground-based spectrographs allows for a full resolution of the line core, which not only gives the detection of sodium, but also the shape of the line. The detection of neutral sodium from the ground calls for several corrections to be applied. Telluric lines, which are lines in the spectra that originate from the atmosphere of Earth, have to be eliminated from the obtained spectra with the software molecfit [9, 10]. Additionally, one has to show that the observed signal indeed stems from the planet atmosphere [11]. We plan to highlight the different pitfalls in detecting sodium in exoplanetary atmospheres during the presentation.

Broadening of the Feature

The main result in Seidel et al. 2019 [7] is the significant broadening of the sodium feature compared to the response function of the instrument (see Fig. 1). A similar broadening effect was found in other Hot Jupiters, such as HD 189733b, where the sodium feature probes altitudes far above the assumed surface. This feature can be explained by thermal broadening from a ultra-hot atmosphere, fast winds, or their combination [5, 7]. We developed a retrieval tool to disentangle between these processes and derive the atmospheric properties from fits to the sodium lines.

Line Retrieval on the Sodium Doublet

Applying a nested sampling retrieval method to the sodium doublet allows studying different possible dynamic structure of the thermosphere as well as to explore possible temperature pressure profiles.

One can built a forward model from these assumptions to calculate a theoretical transmission spectrum of the atmosphere [8]. Using this framework, we parametrised different temperature pressure profiles and wind patterns throughout the atmosphere, each resulting in different fits to the data. To explore the full parameter space of all variables of interest and to compare the different models between themselves, we coupled the forward model framework with a nested

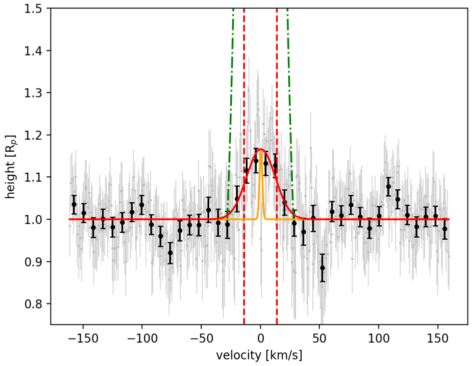

Figure 1: The co-added lines of the HARPS transmission spectrum sodium doublet as a function of velocity. The data is shown in grey and binned x10 in black. Gaussian fit is shown in red with its FWHM marked by the red dashed lines. The HARPS instrumental line spread function is shown in orange and the escape velocity as green dotted-dashed lines. The best Gaussian fit to the data is significantly wider than the instrumental response. Adapted from Seidel et al. 2019 [7].

sampling retrieval. Given that the absorption depth of the line corresponds to an altitude above the surface, different parts of the line corresponds to different altitudes and allow to compare the predictions of models for different atmospheric layers with the observations and rank them via their Bayesian evidence. This technique has been benchmarked on the highly studied Hot Jupiter HD 189733b and showed a strong vertical wind pattern in the upper layers of Hot Jupiter atmospheres. We highlight the advantages of this new approach to link theoretical models with observational data, especially considering its usefulness for studies of the sodium doublet (Seidel et al. 2019b, in prep).

Atmospheric Structure of Ultra Hot Jupiters

Using the unique structure of the thermosphere in comparison to lower layers of the atmosphere, we can show for the first time that models taken from literature [12, 13] for the lower layers of the atmospheres are complementary to more volatile wind patterns and temperature profiles in the higher parts of the atmosphere. Indeed, application of this method shows that the current best fit to the data for HD 189733b, our benchmark case, favours the lower atmospheric profile of super-rotational winds from Flowers et al. 2019 [13] while adding high vertical outbound winds in the higher atmosphere and a temperature gradient to this existing model.

Summary

The broadened sodium features allow us to probe up to the thermosphere and offer observation-based models for the atmospheric structure of Hot Jupiters. We propose different wind and temperature profiles which are then evaluated via a nested sampling retrieval method. Our work has shown that these highly irradiated worlds can feature strong outbound winds in the upper layers of their atmospheres and provides an interesting insight into ultra Hot Jupiters.

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