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SYNERGY BETWEEN STELLAR PHYSICS AND PLANETOLOGY, A PATHWAY FOR HIGH-RESOLUTION SPECTROSCOPY OF EXOPLANET ATMOSPHERE

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Abstract.
Spectroscopy of exoplanet atmospheres at high-resolving powers is a determinant technique for remote atmospheric characterisation of exoplanet atmospheres. However, the non-stationary stellar spectrum affects the position and/of shift of line profiles and creates a non-negligible source of noise that can alter or even prevent detection. In this work, we present three examples of transmission and emission of HD 189733-b and 51 Pegasi b for which the correction for the stellar convection-related activity was included in the analysis. There is a significant improvement in planet detectability when removing the stellar spectrum with our method. Moreover, we briefly present a new approach based on realistic synthetic observations whose innovation and uniqueness is based on the use of 3D hydrodynamical simulations for the atmosphere of both the host star and the planet during the transit

Keywords: stars: atmospheres – Planets and satellites: individual (HD189733b) – Planets and satellites: individual (51 Peg) – Techniques: spectroscopic

1 Introduction

High-resolution spectroscopy (HRS) at resolving powers $R > 25000$ is a determinant technique for remote atmospheric characterisation of exoplanet atmospheres. HRS allows to partially resolve the molecular dense forest of lines and to robustly identify them by line-matching techniques such as cross-correlation. This technique already led to the detection of molecular (CO, H_2O, CH_4, HCN, TiO) and atomic (H, He, K, Na, Mg, Fe, Ti) species in a dozen exoplanets (e.g., Birkby 2018). Secondly, the Doppler shift experienced by the planet during its orbit allows to solve non-transiting systems (e.g., Brogi et al. 2012). Eventually, line shift and broadening is also important to constrain planetary atmospheric winds (Louden & Wheatley 2015; Brogi et al. 2016; Flowers et al. 2019).

HRS technique is currently performed with different infrared spectrographs mounted at large and medium-size telescope facilities and a bright future is forehead with the advent of visible and infrared ELT instruments HIRES (Marconi et al. 2021), METIS (Brandl et al. 2016), and HARMONI (Thatte et al. 2016), with a complete new window open in the field of the combination of high-dispersion spectroscopy with high contrast imaging (Snellen et al. 2015; Houllé et al. 2021).

In this context, the non-uniformity of the planet-hosting stars is a potential source of spurious signals, which can severely complicate the interpretation of exoplanet spectra (Chiavassa et al. 2017; Cegla et al. 2019; Chiavassa & Brogi 2019; Dravins et al. 2021). Stars are not smooth. Their photosphere is covered by a granulation pattern associated with the heat transport by convection (Nordlund et al. 2009), whose temporal and spatial variability depends on the stellar parameters. The related activity (in addition to other phenomena such as magnetic spots, rotation, dust, etc.) has an impact in stellar parameter determination (Bigot et al. 2011; Creevey et al. 2012; Chiavassa et al. 2012), radial velocity (Bigot & Thévenin 2008; Chiavassa et al. 2011; Allende Prieto et al. 2013), chemical abundances determinations (Asplund et al. 2005, 2009; Caffau et al. 2011), photometric colours (Chiavassa et al. 2018; Bonifacio et al. 2017), and on planet detection (Magic et al. 2015; Chiavassa et al. 2017).

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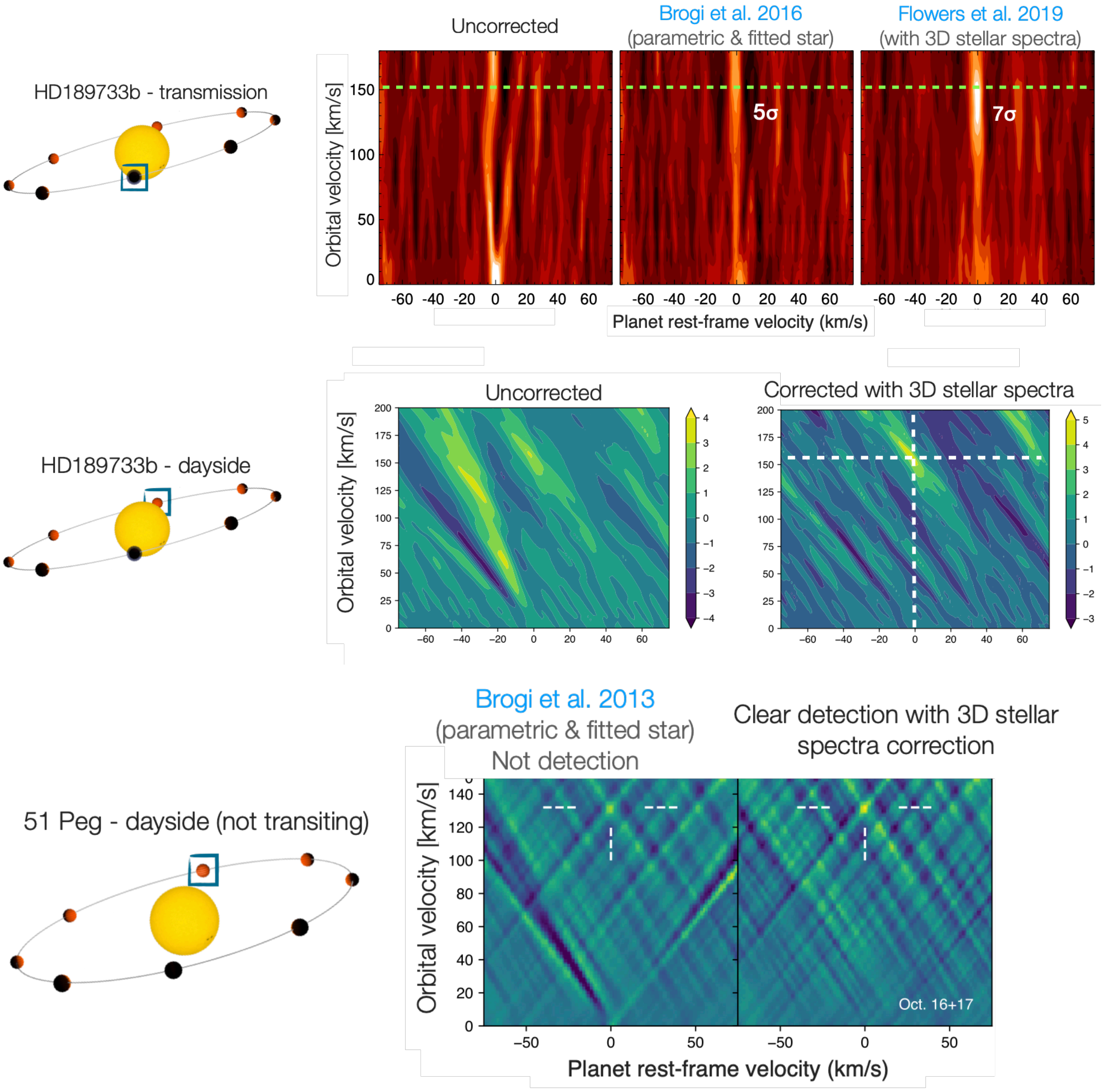

Fig. 1. Total cross-correlation signal, as a function of stellar removal applied to data, from carbon monoxide in transmission spectrum of HD 189733 b (*Top row*), HD 189733 b emission spectrum (*Central row*), and 51 Pegasi b (*Bottom row*). The dashed lines indicate the signal at expected planet maximum orbital velocity ($K_{\rm P} \sim 151$ km s^{-1}). The leftmost sketch displays the configuration of the transit. The Images are from Chiavassa & Brogi (2019).

2 Method

The method used here is based on the pioneering detection of carbon monoxide with HRS cross-correlation (Snellen et al. 2010) with later improvements in several works (e.g., Brogi et al. 2012, 2013). One ultimate aim is the retrieval of exoplanetary temperatures and abundances (Brogi & Line 2019). In this context, the correction for the host star convection-related activity was included for the first time in Chiavassa & Brogi (2019), and we resume here few details concerning the stellar spectra used.

The stellar photosphere are simulated using non-local, three-dimensional, ab initio radiative hydrodynamical (RHD) simulations that cover a substantial portion of the Hertzsprung-Russell diagram (the Stagger-grid, Magic et al. 2013). Afterwards, we used the 3D pure-LTE radiative transfer code Optim3D (Chiavassa et al. 2009) to compute synthetic spectra from the snapshots of different stellar types. To account for center-to-limb distribution, we computed spectra for ten box tilting angles and four azimuths rotations. The constant resolving power used $\lambda/\Delta\lambda = 300\,000$ and the range covered is 22 850 to 23 900 Å, (for mote details, see Chiavassa et al.

2018; Chiavassa & Brogi 2019).

3 Time-differential high-dispersion spectroscopy of CO lines in the K band: three examples

3.1 Transmission spectrum of the exoplanet HD 189733 b

We present one example from Chiavassa & Brogi (2019) to which we point the reader for further details. Fig. 1 (*top row*) displays the significant contaminant stellar contamination (first panel). Brogi et al. (2016) achieved to pinpoint the CO planetary absorption at 5σ using parametric ad-hoc modelisation to account for the stellar correction, albeit with a remaining residual signal from the star (central panel). The use of 3D RHD synthetic spectra (rightmost panel) brought a much better correction and resulted in a unique and unambiguous identification of the planetary signal in CO alone (Flowers et al. 2019). This improvement is reflected into a refined inference on the rotational rate and wind speed of exoplanet HD 189733 b.

3.2 Emission spectra of HD 189733-b and 51 Pegasi b

A second example comes again from HD 189733-b during its orbital phases comprises between 0.38 and 0.48 and analyzed initially by de Kok et al. (2013). Fig. 1 (*central row*) shows that after a quantitative correction with 3D RHD stellar spectra, we recover the signal of the exoplanet in CO at a S/N=4.5, consistent with de Kok et al. (2013), and no stellar residual above the S/N = 3. Also in this case, the uncorrected signal by the stellar spectrum would be completely outshone by stellar residuals, preventing the detection.

The last example concerns the data described in Brogi et al. (2013) for 51 Pegasi b. Fig. 1 (*bottom row*) displays that when the stellar spectrum is removed, the planet remains the only unambiguous source detected. This results, detailed in Chiavassa & Brogi (2019), is a clear improvement from the non-detection originally reported by Brogi et al. (2013).

4 The future: coupling stellar and planet dynamics during transits

We are developing a new approach (Maimone 2021) based on realistic synthetic observations whose innovation and uniqueness is based on the use of 3D hydrodynamical simulations for the atmosphere of both the host star (Stagger-code, Nordlund et al. 2009) and the planet (hot jupiters grid computed with MITgcm, Parmentier et al. 2016) during the transit. This is done using an updated version of the post-processing radiative transfer code Optim3D (Chiavassa et al. 2009). The code takes into account, simultaneously, the stellar and planetary dynamics. They influence the shape, shift, and asymmetries of spectral lines, and not rarely of the same specie (Fig. 2). This new method will be used to interpret HRS data to extract extremely useful information either for the characterization of the stellar parameters and metallicity and for the planet dynamics and composition.

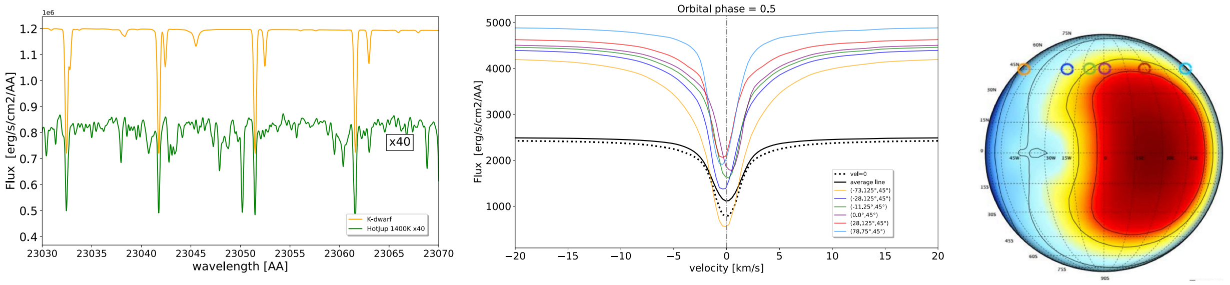

Fig. 2. *Right panel:* example of stellar (K dwarf from Chiavassa et al. 2018) and scaled hot jupiter with T_{eq}=1400 K (Parmentier et al. 2016) spectra in K band computed with the new version of Optim3D. Both objects show the same CO spectral features. *Central panel:* one particular hot jupiter CO line computed for different atmospheric regions. *Right panel:* Temperature map of the hot jupiter with highlighted areas (colored circles) used to compute CO lines in central panel.

With this tool in hands, we will have access to the whole comprehension of the transit phenomena with a large impact on different areas of astrophysics from exoplanets to stars: e.g., reliable study on the impact of stellar parameters and activity as well as a full characterization of the atmosphere of the planet, from molecular detection to the abundance of their elements.

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