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Stellar activity effects on the properties of exoplanetary atmosphere

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Abstract. Exoplanet atmospheres are our only window to study the physical and chemical processes that occur on distant worlds. Such processes are important tracers of the origins of planetary systems. These are also paramount to understand how common or unique are the conditions that lead to the emergence of life, which can leave precise spectroscopic traces in exoplanetary atmospheres. Transmission spectroscopy is a very effective technique for probing and measuring the composition and properties of exoplanet atmospheres. This technique consists of taking a spectra during a planetary transit in front of its host star. During the transit, a small fraction of the stellar radiation is filtered through the planet's atmosphere, where it is only partially absorbed. The absorption will be wavelength dependent due to the scattering properties of atoms and molecules present in the planetary atmosphere. At the wavelength of a strong atomic or molecular transition, the atmosphere is more opaque and the radius of the planet appears larger. Thus, transmission spectrum of the planet's atmosphere provides clues about its composition. One of the main limitations of this technique is the stellar activity that can lead to a significant underestimation or overestimation of the ratio of planet and stellar radius as a function of wavelength. Therefore, we will quantitatively study the impact of stellar activity, such as the presence of spots, on the transmission spectrum of exoplanets.

Resumo. Atmosferas de exoplanetas são nossa única janela para estudar os processos físicos e químicos que ocorrem em mundos distantes. Tais processos são importantes traçadores das origens de sistemas planetários. Estes também são fundamentais para entender quão comuns ou únicas são as condições que levam ao surgimento da vida, que podem deixar traços espectroscópicos precisos em atmosferas exoplanetárias. A espectroscopia de transmissão é uma técnica muito eficaz para sondar e medir a composição e as propriedades das atmosferas dos exoplanetas. Esta técnica consiste em obter um espectro durante um trânsito planetário em frente à sua estrela hospedeira. Durante o trânsito, uma pequena fração da radiação estelar é filtrada pela atmosfera, onde é apenas parcialmente absorvida. A absorção será dependente do comprimento de onda devido às propriedades de dispersão dos átomos e moléculas presentes na atmosfera. No comprimento de onda de uma forte transição atômica ou molecular, a atmosfera é mais opaca e o raio aparente do planeta é maior. Assim, o espectro de transmissão da atmosfera do planeta fornece pistas sobre sua composição. Uma das principais limitações desta técnica é a atividade estelar que pode levar a uma significativa subestimação ou superestimação da razão entre o raio do planeta e o raio estelar em função do comprimento de onda. Portanto, estudaremos quantitativamente o impacto da atividade estelar, como a presença de manchas, no espectro de transmissão de exoplanetas.

Keywords. Planets and satellites: atmospheres – Stars: activity – Techniques: spectroscopic

1. Introduction

Exoplanets are now known to be omnipresent in our Galaxy. As the catalog of known exoplanets grows, the potential habitability of planets discovered around their stars has been of fundamental interest for astrophysicists.

Transmission spectroscopy (multi-band photometry) of transiting exoplanets is the most powerful technique for studying the structure and composition of their atmospheres. We can learn the details about exoplanets and their parent stars through observations of their combined light. Nonetheless, in most transmission spectroscopy studies, the impact of stellar activity has not been fully taken into account yet. Thus our aim is to determine the influence of stellar activity on the retrieved transmission spectra, acquired by stellar light curves during planetary transits. It is essential to quantify the impact of stellar contamination on transmission spectroscopy and develop methods to mitigate it. The analysis of the data, obtained mostly by HST and JWT, requires an accurate transit light-curve modeling, for which stellar activity must be taken into account.

2. Transmission Spectroscopy

Transmission spectroscopy by a planet transiting its host star is the most powerful technique for studying the structure and composition of their atmospheres. The scenario sketched in Figure 1 shows a trapezoidal approximation of the flux variation during planetary ingress and egress, which is linearly time-varying. However, this is not true, mainly because the stellar brightness is not distributed uniformly across the stellar disk, but exhibits limb darkening in visible light. In this work, we use the four parameter non-linear limb-darkening model of Claret 2000 given by:

$$\frac{I(\mu)}{I_0} = \sum_{n=1}^{4} c_n (1 - \mu^{n/2}) \tag{1}$$

where c_n are the limb darkening coefficients, I_0 is the specific intensity at the center of the disk, and $\mu = \cos\gamma$ (γ being the angle between the line of sight and the emergent intensity).

Since the detection of the first exoplanet atmosphere (Charbonneau et al. 2002), transit observations allowed the characterization of a plethora of distinct exoplanet's atmospheric molecules, clouds, and/or hazes. The main idea behind transmission spectroscopy lies in high-precision observations of transits at different wavelengths. At wavelengths where the atmosphere is more opaque due to absorption by atoms or molecules, the planet blocks more of the stellar flux. As can be seen in Figure 2, absorption and scattering in the exoplanet's atmosphere change the transit depth as a function of wavelength.

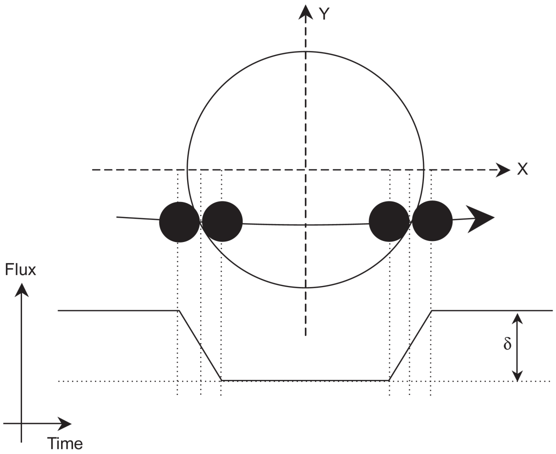

Figure 1. Illustration of a transit, taken from Winn 2010.

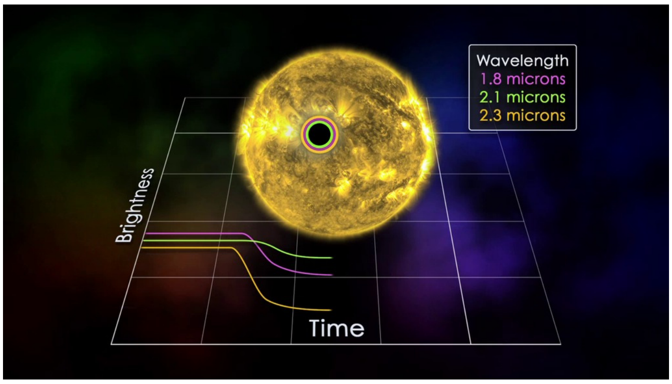

Figure 2. Wavelength-dependent light curves of a star during an exoplanet transit.

3. Preliminary results

To achieve our objectives, we have modified the `ECLIPSE`[1] code (Silva 2003) by incorporating wavelength dependence, to reproduce a large number of transit light curves for different exoplanets and stellar spectral types.

It is noteworthy that the aforementioned limb darkening coefficients, c_n, were obtained from theoretical models calculated using the `ExoCTK` (Bourque et al. 2021) limb-darkening tool.

The parameters of HD 69830 and HD 69830 b were used to perform the simulations ($R_\star = 0.89\,R_\odot$, $M_\star = 0.86\,M_\odot$, $R_p = 0.28\,R_J$, $M_p = 0.03\,M_J$). We assume that both the spot and the stellar surface radiate as blackbodies. The stellar spot was modeled as a circular dark feature with a radius of $R_{spot} = 0.025R_p$ in the case of starspot occultation and $R_{spot} = 0.025\,R_p$ for an unocculted spot.

The code yields the results for the models of occulted (Figure 3) and unocculted starspots (Figure 4) by a transiting exoplanet. As can be seen in Figure 4, the second-order polynomial fitting is in agreement with Equations 5 and 6 from Rackham 2019.

4. Final remarks

Our preliminary results indicate the potential importance of considering the stellar activity contamination on space-based transmission spectra. Thus care is necessary when analyzing transmission spectra to mitigation the effects of active regions.

Regarding the code, it will be improved with the addition of not only starspots, but also faculae (bright features on the stellar photosphere). Besides, in the near future, we will test the model with data from space-based observatories, such as Hubble Space Telescope and James Webb Telescope.

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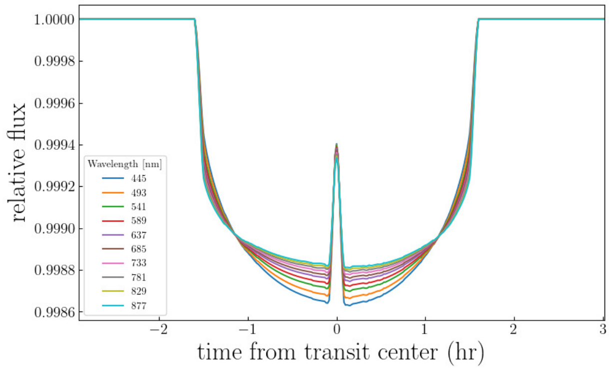

Figure 3. Wavelength-dependent light curves of a starspot occultation.

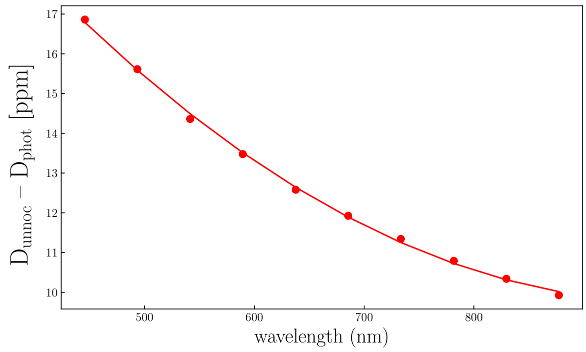

Figure 4. Differences between the transit depths of an unocculted starspot by a transiting exoplanet and the unspotted photosphere.

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[1] https://github.com/Transit-Model-CRAAM/pipelineMCMC