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Influence of transit latitude on planetary transmission spectra

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Abstract. Transmission spectroscopy is a very effective technique for probing and measuring the composition and properties of exoplanet atmospheres. This technique has been successfully applied to a plethora of exoplanets, primarily using HST and JWST. The precise understanding of the wavelength-dependent brightness of the star being occulted requires modeling efforts to understand its heterogeneity. An important parameter in the transmission spectra is the depth of the observed planetary transit. To simulate planetary transits taking into consideration the activity of the star, that is, spots on its surface, we have developed the ECLIPSE-Xλ code by incorporating wavelength dependence onto the original ECLIPSE program. A large number of transit light curves were simulated for different exoplanets and stellar spectral types. Here we present a novel study which considers in the modelling the stellar transit latitude of the planetary orbit. This parameter plays a substantial role in estimating the transit depths.

Resumo. A espectroscopia de transmissão é uma técnica muito eficaz para investigar e medir a composição e as propriedades das atmosferas de exoplanetas. Essa técnica tem sido empregada com sucesso a uma grande quantidade de exoplanetas, principalmente usando o Hubble Space Telescope (HST) e o James Webb Space Telescope (JWST). A compreensão precisa da dependência do brilho com o comprimento de onda da estrela sendo ocultada requer esforços de modelagem para entender sua heterogeneidade. Um parâmetro importante nos espectros de transmissão é a profundidade do trânsito planetário observado. Para simular trânsitos planetários levando em consideração a atividade da estrela, ou seja, manchas em sua superfície, desenvolvemos o código ECLIPSE-Xλ, incorporando a dependência do comprimento de onda no programa original ECLIPSE. Foram simuladas uma grande quantidade de curvas de luz de trânsito para diferentes exoplanetas e tipos espectrais estelares. Aqui apresentamos um novo estudo que considera, na modelagem, a latitude de trânsito estelar da órbita planetária. Esse parâmetro desempenha um papel substancial na estimativa das profundidades de trânsito.

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

1. Introduction

Exoplanets have become recognized as ubiquitous throughout our galaxy. As the catalog of identified exoplanets expands, the inherent interest of astrophysicists has shifted towards exploring the potential habitability of planets orbiting distant stars.

The transmission spectroscopy stands out as the most powerful technique for investigating the structure and composition of the atmospheres of transiting exoplanets. Valuable insights into the intricacies of both exoplanets and their parent stars can be obtained through the careful examination of their combined light. However, in the majority of transmission spectroscopy studies, the impact of stellar activity has not been fully taken into account. Furthermore, the latitude at which the planet transits carves out the shape and characterizes the slope of the transmission spectra. Thus our aim is to investigate the intricate interplay between transit latitude variations and the presence of unocculted spots in estimates of transit depth of planetary transmission spectra.

2. Model description

The ECLIPSE-Xλ[1] ia a transit modeling tool constructed upon the groundwork of the ECLIPSE[2] model originally proposed by Silva (2003). Expanding the functionality of ECLIPSE, ECLIPSE-Xλ allows for the simulation of transit light curves across a wide range of wavelengths.

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

The model ECLIPSE-Xλ considers several stellar limb darkening functions, such as a quadratic function (Manduca et al. 1977; Wade & Rucinski 1985), logarithmic (Klinglesmith & Sobieski 1970), square root (Diaz-Cordoves & Gimenez 1992), three-parameter (Sing et al. 2009), and four-parameter (Claret 2000).

The intensity ratio between the spot/facula and the stellar surface is estimated assuming that both emit radiation as blackbodies. Thus the spot/facula intensity can be determined using the following equation:

$$\frac{I_{\mathrm{spot/fac}}}{I_{\mathrm{star}}} = \frac{\exp\left[hc/(\lambda\, K_{\mathrm{B}}\, T_{\mathrm{star}})\right] - 1}{\exp\left[hc/(\lambda\, K_{\mathrm{B}}\, T_{\mathrm{spot/fac}})\right] - 1}\ , \tag{1}$$

where h is the Planck constant, K_{B} is the Boltzmann constant, λ is the wavelength of observation, T_{star} is the star effective surface temperature and $T_{\mathrm{spot/fac}}$ is the starspot or facula temperature. Rackham (2019) established a linear relationship between photosphere, T_{star}, and spot, T_{spot}, temperatures across a range of G2 to M0 stars, expressed as

$$T_{\mathrm{spot}} = 0.418 \times T_{\mathrm{star}} + 1620\,\mathrm{K}\,. \tag{2}$$

These temperatures were derived according to the work of Berdyugina (2005).

3. Results

The exoplanet 55 Cnc e was chosen for this study based on its orbital parameters. The orbital inclination angle is defined as the inclination angle between an observer's line of sight and the perpendicular to the orbital plane of the planet. The ratio of the

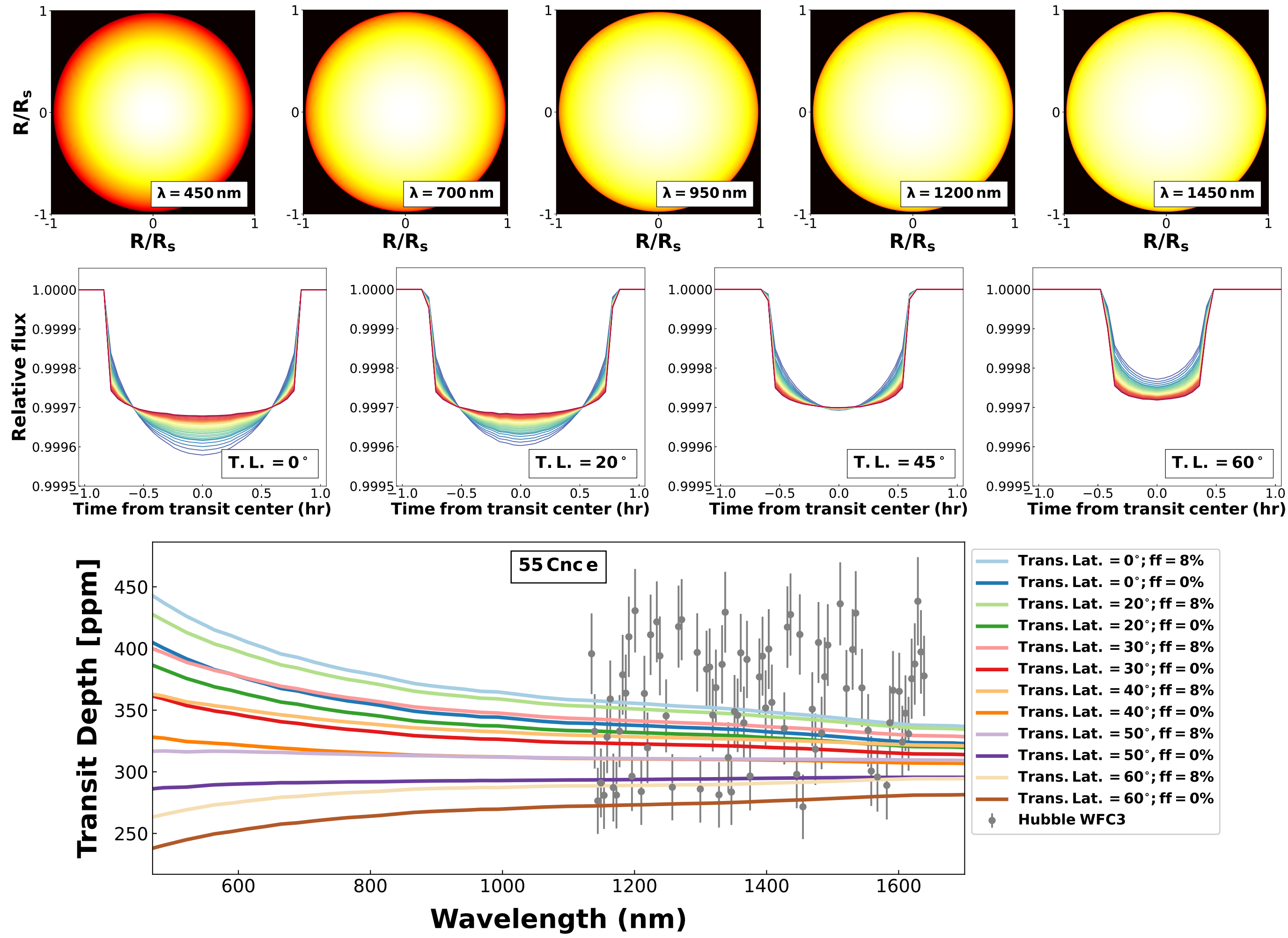

Figure 1. 2D image of the limb-darkened stellar disc. The observed variations are induced by simulations at different wavelengths, which correspond, from right to left: 450 nm, 700 nm, 950 nm, 1200 nm, 1450 nm.

radii of the star and the planet, R_s and R_p, respectively, the orbital semi-major axis, a, as well as the orbital inclination angle, i, can be measured from the transit shape. Hence, the projected latitude of a planet transit, T.L., with respect to its parent star can be expressed as

$$\text{T.L.} = \arcsin\left(\cos i \times \frac{a}{R_s}\right) . \quad (3)$$

Inasmuch as the exoplanetary systems present distinct values of stellar radii, inclination angles and semi-major axes, they transit at different latitudes (T.L. given by Equation 3) relative to their host stars. In the simulations results shown in Figure 1, we selected an exoplanet, 55 Cnc e, which transits at 24° in relation to its host star. The simulations specifically concentrate on modeling a star with unocculted spots and the corresponding unspotted photosphere at various transit latitudes.

4. Discussion and conclusions

The transit latitudes for the exoplanet 55 Cnc e are varied in these scenarios, as shown in the lower panel of the Figure 1. The variation in transit depth is pronounced across different wavelengths, especially in the optical. Hence, the way we interpret the exoplanetary atmosphere, particularly in terms of the presence or absence of clouds or hazes, can vary significantly depending on the planet's transit latitude.

In the NIR range, there is only a minimal discrepancy, less than a few tenths, in the transit depths between the models of photosphere with active regions and unspotted photosphere. None the less, the presence or absence of stellar activity, together with the transit latitude, can play a crucial role in the interpretation of data from JWST, which is notably more sensitive than HST/WFC3.

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