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The limb darkening on the detection of exoplanets and exomoons

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Abstract. Stellar limb darkening is an important parameter in the analysis of transits light curves, whether from systems consisting of binary stars, planets or even moons. The depth of the transit on the light curve is primarily determined by the ratio of the radius of the second body to the radius of the star. By modeling the planetary transit, we can retrieve information about the limb darkening coefficients and better understand the brightness profile of the star. The general effect of limb darkening is the change in the depth of the light curve as a function of the impact parameter and profile modification of the transit. In this work, we present simulations with different limb darkening law prescriptions and related consequences for detecting transit events. For this purpose, we simulate various systems with the main predefined parameters, such as radius fraction, major half axis, orbital period, inclination, eccentricity, and limb darkening coefficients of various laws, and apply the noise and systematic errors of various space missions (Kepler, TESS and PLATO). The idea is to recover the original system in a blind procedure. In this work, we investigate the advantages and disadvantages of an *a posteriori* definition of limb darkening coefficients in the study of transits.

Resumo. O escurecimento do limbo estelar é um importante parâmetro na análise de curvas de luz de eclipses, sejam estes de sistemas compostos por estrelas binárias, planetas ou mesmo luas. A profundidade do trânsito na curva de luz é primariamente determinada pela razão entre o raio do segundo corpo e o raio da estrela. Através da modelização do trânsito planetário, podemos recuperar informações a respeito dos coeficientes do escurecimento do limbo e entender melhor o perfil de brilho da estrela. O efeito geral do escurecimento do limbo é a alteração da profundidade da curva de luz em função do parâmetro de impacto e modificação do perfil do trânsito. Neste trabalho apresentaremos resultados de simulações com diferentes prescrições de leis de escurecimento do limbo e consequências para detecções de eventos de trânsito. Para isso, simulamos sistemas com os principais parâmetros pré-definidos, tais como fração dos raios, semi-eixo maior, período orbital, inclinação, excentricidade e coeficientes do escurecimento do limbo de várias leis, e aplicamos os ruídos e erros sistemáticos de diversas missões espaciais (Kepler, TESS e PLATO). A ideia é de recuperarmos o sistema original em um procedimento "blind". Neste trabalho investigamos vantagens e desvantagens de uma definição a *a posteriori* dos coeficientes de escurecimento do limbo no estudo de trânsitos.

Keywords. Stars: fundamental parameters – Planets and satellites: detection – Methods: data analysis

1. Introduction

Within the occurrence of State-of-art telescopes such as Kepler and TESS a *'brust'* in the search to some other habitable astro in the universe has happened, when this work was written there were more than 4,100 exoplanets confirmed by the NASA catalog, while no exomoons were confirmed yet. Alongside this search, the precision of the light curve is getting better day after day, and many techniques have been applied in order to resolve the planetary systems, modeling the transit light curve is a great weapon already widely used in the literature that we also base our work on, but in the perspective of sharpening the limb darkening coefficients from the literature. From this angle, deciding to use limb darkening in *a priori* or a *a posteriori* prescription is a relevant point today.

For almost every star (except for white dwarfs) the distribution of intensity shows a darkening toward the stellar limb, which could be easily proven by the Sun. This effect, usually called limb darkening, depends on the surface temperature of the underlying stars and is difficult to measure when the stellar disk remains unresolved. The best way to model the Limb Darkening has been one of the problems on the stellar astrophysics.

2. Methodology

Many different models have been proposed, one of the most simple is the Linear Law, introduced as :

$$I(\mu) = 1 - u(1-\mu) \tag{1}$$

Although this formulae is still applicable for some less precision light curves or when trying to describe more specific effects such as the Rossiter-McLaughlin effect, more sophisticated models were required to better characterize the stellar atmosphere. Nowadays, most commonly used laws are:
The quadratic law:

$$I(\mu) = 1 - u_1(1-\mu) - u_2(1-\mu)^2 \tag{2}$$

The square root law:

$$I(\mu) = 1 - u_3(1-\mu) - u_4(1-\sqrt{\mu}) \tag{3}$$

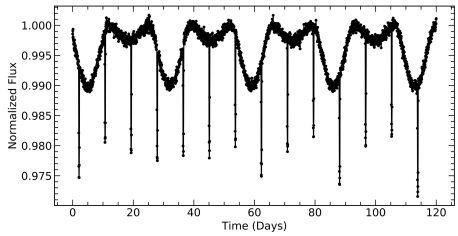
And the logarithm law:

$$I(\mu) = 1 - u_5(1-\mu) - u_6\mu\ln\mu \tag{4}$$

Where $\mu = \cos\theta$ and $u_1, u_2, u_3, u_4, u_5, u_6$ are the respective limb darkening coefficients, while θ is defined as the angle between the observer and the normal to the stellar surface. Is worth to say that these formulas are usually written as $\frac{I(\mu)}{I(1)}$, but is trivial that $I(1) = 1$ for all laws above. For more details check Pál (2008)

In our simulation, we use the ellc algorithm by Maxted (2016) to generate the stellar rotation of 2 star spots, both with quadratic limb darkening coefficients but in different longitudes, the starspots had 2,5% and 5% of the stellar radius. Furthermore, to simulate the planetary transits, we made use of the batman-package from Kreidberg (2015), which is a well-known implementation of the transit equations from Mandel and Agol (2002)

FIGURE 1. Raw synthetic Data



in the *C* language on a python interface. Besides all limb darkening laws cited above, batman also supports parallelization, secondary transits, and even a user-defined limb darkening law. In our system, the synthetic planet was simulated with quadratic limb darkening. Afterward creating our synthetic data, we added some Kepler-like noise, ending with the light curve (see Figure 1).

Then, we began our *blind* procedure, knowing only the light curve represented in Figure 1, we made some data treatment and were able, using the Lomb-Scargle periodogram to determine the period of stellar rotation and the phase-folded graph (See Figure 2). And also, by fitting and removing the stellar rotation from the raw light curve, we were able to do the same analysis for the Planet (See Figure 3).

Now, we can apply the Markov chain Monte Carlo (MCMC) simulation in order to obtain the distribution of probability of each free parameter in our model, in this work we have a special desire for both limb darkening coefficients. As we already have a great estimate of the planetary period, form the GLS, we can let the period fluctuate on a little 'ball' around our initial guess. Finally, we used the emcee package from Foreman-Mackey et al. (2013) to set and run our simulations, using the Metropolis–Hastings algorithm to select which move was going to be accepted. Obtaining the Figure 4 as the main result of our work.

3. Summary and discussion

We have seen that using the limb darkening coefficients *a posteriori* is an alternative, and considering the results achieved by Csizmadia et al. (2013), where the author affirms that if *a priori* coefficients are adopted according to some theoretical predictions, the inconsistencies of the tables do not allow to reach accuracy in the planetary radius of better than 1-10% if the star's effective temperature is higher than 5000 K (below that temperature may contain even 20% error). If we apply these values to Kepler-1625-b's system (where there is a great discussion on whether or not there is an exomoon detection), the error on the planet radius would be up to 30% of the radius of the supposed moon. Thus, a great implication on the exomoon detection.

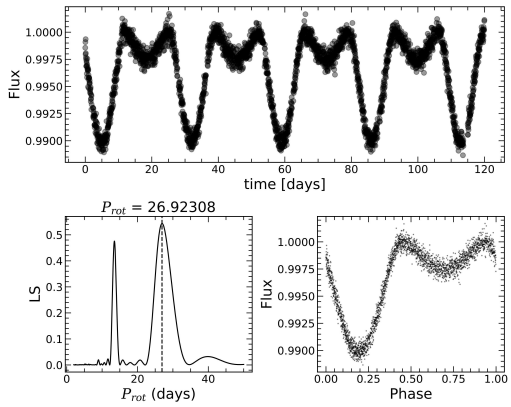


FIGURE 2. Rotation analysis

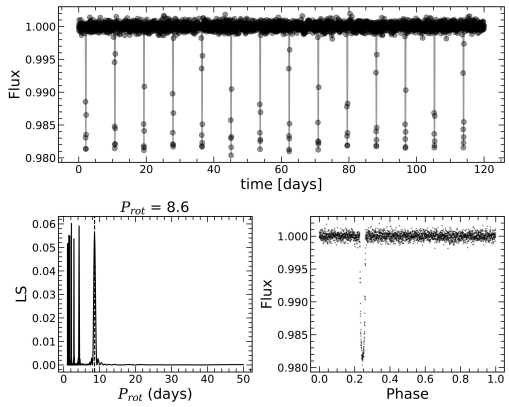


FIGURE 3. Planet Analysis

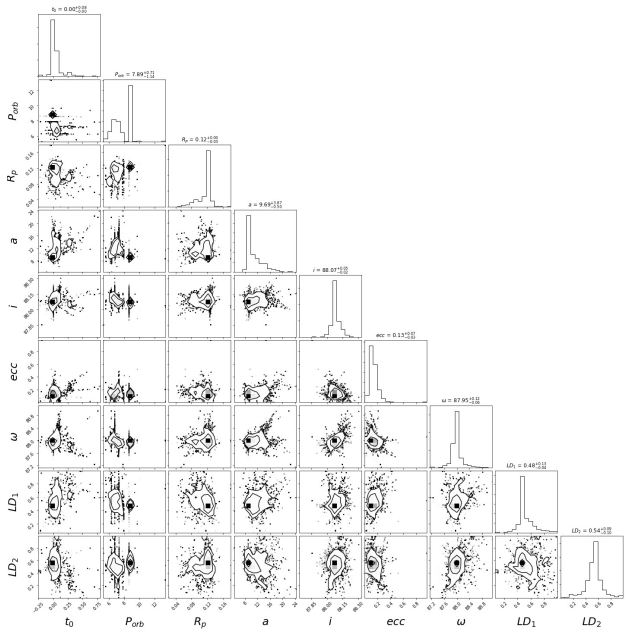


FIGURE 4. Corner plot: *Posterior* Distribution

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