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Simulations of stellar activity in Python and its impacts on the star's light curve

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Abstract. Since the initial identification of exoplanets (planets located outside our Solar System) in the 1990s, and the first detection of a planetary transit in 2000, the transit technique for detecting planets has been widely used by several space observatories, such as Kepler and TESS. By observing transits in the luminosity of an exoplanet's host star, it is possible to deduce some parameters of the planet, such as its radius, orbital inclination, and orbital semi-axis. However, a host star can exhibit active regions on its surface, which cause small fluctuations in luminosity when the planet passes in front of these spots. These variations in the light curves during the transit result in a less precise and even underestimated determination of the planetary parameters. Therefore, it is essential to employ techniques for analyzing and modeling these starspots to more accurately estimate the characteristics of exoplanets, taking into account the changes caused by the star's activity. In this project, a set of Python programs was developed to calibrate, analyze, and model the variations in light curves due to the presence of active regions and fluctuations on their surface, with the aim of improving the accuracy of planetary and orbital parameters, as well as the correlation between impacts suffered by the planet's atmosphere and stellar activity.

Keywords. Stellar Activity, Exoplanets, Light curves, Transit Method

1. Introduction

The transit method has become the most productive technique for exoplanet discovery, accounting for approximately 61% of all confirmed detections (4,560 planets) Extrasolar Planets Encyclopaedia (2024). Pioneered in 2000 and heavily utilized by space telescopes like Kepler and TESS, this approach allows scientists to infer key planetary parameters– such as radius, orbital inclination, and semi-major axis by analyzing the dip in a star's brightness during a transit Perryman (2011).

Light curve analysis examines how planetary parameters affect the transit profile. Variations in planet radius lead to changes in transit depth, while the orbital semi-major axis influences the duration of the transit. Similarly, orbital inclination modifies the overall shape of the light curve Silva (2003).

The star Kepler-423, a very active star characterized by the presence of spots on its surface, hosts the gas giant Kepler-423 b, which transits every 2.7 days. Observations from the Kepler mission confirmed the existence of active regions with spots and faculae, making this system particularly suitable for studying the effects of stellar activity Hazra et al. (2021).

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Table 1. Results of MCMC fits

Transit parameters			Spot parameters		
Parameter	**Prior**	**Posterior**	**Parameter**	**Prior**	**Posterior**
u1	0.4650	$0.46^{+0.09}_{-0.14}$	Radius (R_{star})	0.07	$0.08^{+0.09}_{-0.14}$
u2	0.1518	$0.09^{+0.03}_{-0.4}$	Intensity	0.5	$0.52^{+0.03}_{-0.4}$
Semi-axis (au)	0.03585	$0.04^{+0.01}_{-0.1}$	Latitude (°)	-7.86	$-7.61^{+0.01}_{-0.1}$
Inc angle (°)	88.97	$88.97^{+0.03}_{-0.05}$	Longitude (°)	15.29	$7.23^{+0.03}_{-0.05}$
Radius (R_{Jup})	1.192	$1.06^{+0.06}_{-0.05}$			

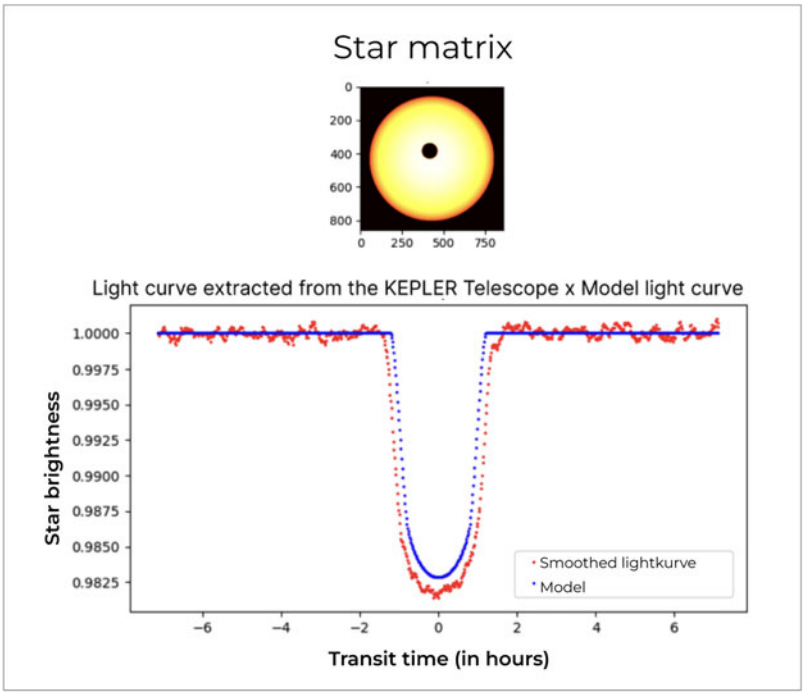


Figure 1. Kepler-423 light curve transit observed by the Kepler telescope (red) and the model of a spotless star using the parameters given in Extrasolar Planets Encyclopaedia (2024) (blue).

2. Transit Model and the ECLIPSE Program

The ECLIPSE† program, developed in Python, was employed to model stellar light curves both with and without incorporating surface activity phenomena. This tool allows for the simulation of planetary transits, incorporating features such as planets, moons, faculae, and spots, enabling a detailed analysis of their impact on the resulting transit signatures Silva & Valio (2020). The ECLIPSE program processes the light curves by first retrieving data from the Kepler, K2, and TESS missions via the LightKurve library Lightkurve Collaboration et al. (2018). It then generates a theoretical transit model based on user-defined system parameters and performs a model fit against the observed light curve.

An example of the model (blue curve) is shown in Figure 1 where the parameters of the star Kepler-423 and the planet Kepler 423 b were sourced from Exoplanet.EU Extrasolar Planets Encyclopaedia (2024) and are listed as priors in Table 1. As can be seen, the parameters need improvement. A model of a star with a spot and a facula is shown in

† https://github.com/Transit-Model-CRAAM/pipelineMCMC

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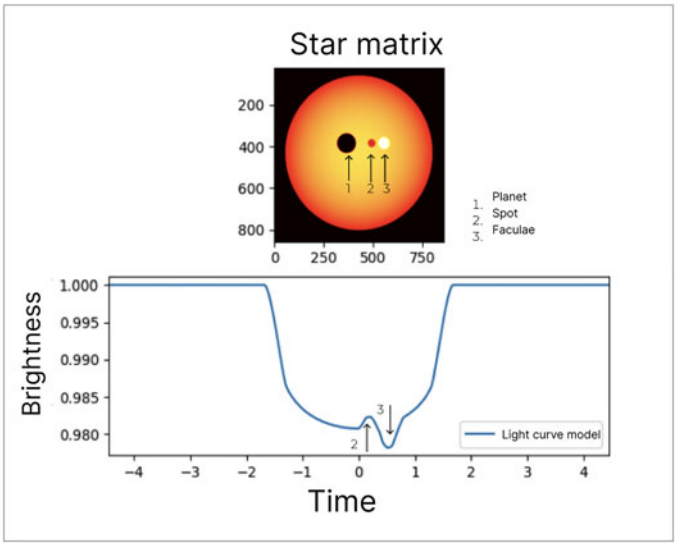


Figure 2. Transit simulation adding a planet (1), a spot (2), and a faculae (3), and their respective changes in the light curve, indicated by the numbered arrows.

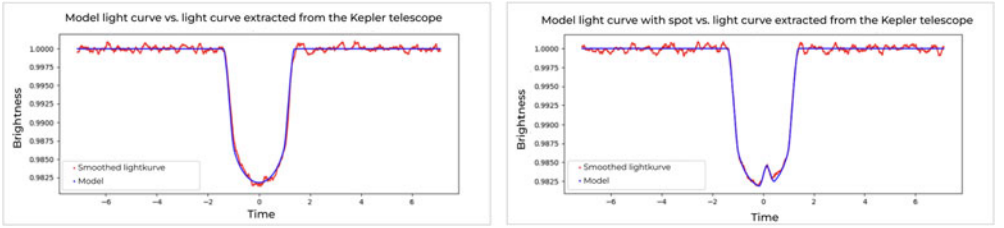


Figure 3. Left: Light curve resulting from the fitting of planet and star parameters (blue curve) compared to the curve downloaded from the telescope (red curve). **Right:** Light curve resulting from the fitting of the parameters of a spot (blue curve) compared to the curve downloaded from the telescope (red curve).

the right panel of Figure 2. The impact of these features on the light curve as they are occulted by the planet during its transit is indicated by the arrows.

For the fitting of the observed light curve with the `ECLIPSE` model, we integrated **parallel C** code into our Python scripts to accelerate matrix generation during MCMC sampling, **resulting in a 50x to 80x performance gain** Pinho, Silva & Valio (2022). The MCMC method is advantageous as it not only fits the model to the data but also yields the uncertainties (upper and lower bounds) for each parameter.

3. Results: Fiting Star and Exoplanets Parameters and Spots

Figure 3 illustrates the complete fitting process. The left panel shows the initial fit of a spotless star model (blue) to the Kepler light curve (red), which determines the host star and planetary parameters (Table 1, third column). Then, these parameters are fixed while another MCMC fit models the stellar spot occultation, the results of which are plotted in the sixth column of Table 1. The result of this two-stage fitting process is a complete model (blue) that closely reproduces the observed Kepler data (red), as shown in the right panel of Figure 3.

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4. Conclusions

The `ECLIPSE` program successfully modeled the Kepler-423 star-planet system by simulating its transit light curve and comparing it with Kepler telescope data. Using an MCMC algorithm, it accurately fit the stellar and planetary parameters, including the effects of starspots, and quantified their uncertainties. The program's efficiency is significantly enhanced by parallel C integration, achieving up to an 80x speed-up in simulations. This adaptable method is also suitable for characterizing other exoplanetary systems.

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