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Stellar activity simulations and their impact on the light curve of the star HD 189733 A

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Abstract. The detection and characterization of exoplanets rely on precise measurements of their host stars' light curves, which can be significantly affected by stellar activity. Starspots, faculae, and other surface features introduce brightness variations that can influence the determination of planetary parameters such as radius, orbital inclination, and transit depth. Understanding and mitigating these effects are crucial for improving the accuracy of planetary characterization. In this study, we present a set of Python programs developed to calibrate, analyze, and model variations in the light curve of stars. The model is applied to HD 189733 A, a K-type star transited by the hot jupiter HD 189733 Ab observed by the TESS mission, a good candidate due to its great activity and spots on its surface. The focus of this study was to identify and characterize the signatures caused by stellar activity, particularly the presence of starspots of faculae on the stellar surface. The methodology includes data calibration, transit modeling, and activity characterization to distinguish planetary signals from stellar-induced variations. The results contributed to improve exoplanet parameter estimation, reduce systematic uncertainties, and enhance our understanding of the interplay between stellar magnetic activity and exoplanet detection, particularly for active host stars like HD 189733 A.

Resumo. A detecção e caracterização de exoplanetas dependem de medições precisas das curvas de luz de suas estrelas hospedeiras, as quais podem ser significativamente afetadas pela atividade estelar. Manchas estelares, fáculas e outros fenômenos superficiais introduzem variações de brilho que podem influenciar a determinação de parâmetros planetários como raio, inclinação orbital e profundidade de trânsito. Compreender e mitigar esses efeitos é crucial para melhorar a precisão da caracterização planetária. Neste estudo, apresentamos um conjunto de programas Python desenvolvido para calibrar, analisar e modelar variações nas curvas de luz de estrelas. O modelo foi aplicado a HD 189733 A, uma estrela do tipo K transitada pelo Júpiter quente HD 189733 b, observada pela missão TESS, uma boa candidata devido à sua grande atividade e à presença de manchas em sua superfície. O foco deste estudo foi identificar e caracterizar as assinaturas da atividade estelar, especialmente a presença de manchas e faculas na superfície estelar. A metodologia inclui calibração de dados, modelagem de trânsito e caracterização da atividade para distinguir sinais planetários de variações induzidas pela estrela. Os resultados contribuem para melhorar a estimação dos parâmetros de exoplanetas, reduzir incertezas sistemáticas e aprimorar nossa compreenssão da interação entre a atividade magnética estelar e a detecção de exoplanetas, particularmente para estrelas hospedeiras ativas como HD 189733 A.

Keywords. Photometric – Activity – Data Analysis

1. Introduction

The first exoplanets were discovered in the mid-1990s through the radial-velocity technique, which detects the gravitational influence of a planet on its host star. This method dominated the early years of exoplanet discovery and played a central role in establishing the field. Only in 2000 was the first transiting exoplanet detected, marking the beginning of a new observational era. Since then, the transit technique has become the leading method for identifying exoplanets (The Extrasolar Planets Encyclopaedia 2025), accounting for approximately 75% of the 6,153 known discoveries. Space missions like Kepler and TESS were crucial for this field, allowing fundamental planetary parameters, such as radius, semimajor axis, and orbital inclination, to be deduced from the observed small dips in stellar brightness (Perryman 2011).

Here we developed a set of Python scripts (`ECLIPSE`) (Duque Estrada & Valio 2020) with the aim of modeling and analyzing light curve variations for the star HD189733 A, which hosts the planet HD189733 Ab. The tool is unique in its capacity to simulate spots, faculae, and moons, providing insights into the influence of stellar activity. The ultimate goal is to significantly increase the precision in determining planetary and orbital parameters, refining transit analysis and actively contributing to planetary science.

2. Methodology

The methodology consisted of selecting a target star and analyzing its light curve obtained from TESS planetary transit observations. The transit was then modeled using the `ECLIPSE` script to fit the planetary parameters (Pinho, Duque Estrada & Valio 2022).

2.1. Exoplanet Detection and Light Curve Analysis

Analyzing a star's light curve not only reveals the presence of a planet through the characteristic decrease in stellar flux, but also allows key planetary parameters to be inferred from the shape of the transit profile (Silva 2003):

- **Planet radius:** A larger radius increases the transit depth.
- **Orbital semi-major axis:** A higher value prolongs the transit duration.
- **Orbital inclination:** Shapes the format of the transit light curve.

Spot and Faculae Modeling

The model, shown in Figure 1, incorporates the parameters of the star HD 189733 A and the planet HD 189733 Ab (Table 1), obtained from Exoplanet.EU (The Extrasolar Planets

Encyclopaedia 2025), with the addition of a spot and a facula in the model, which produce impacts on the light curve.

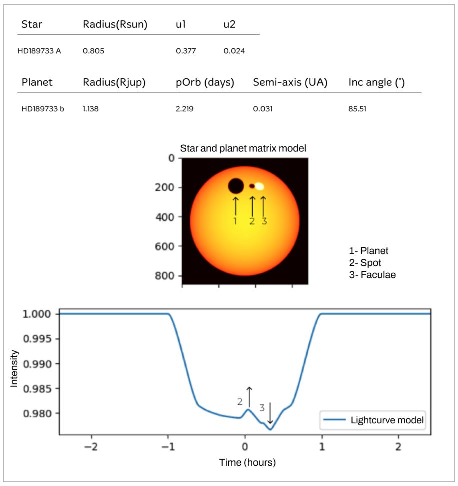

Figure 1. Top panel: Star and planet values used for this model. **Bottom panel:** Transit simulation adding a planet (1), a spot (2), and a facula (3), and their respective changes in the light curve, indicated by the numbered arrows.

2.2. Selection of the Star HD 189733 A

A K-type star, transited by the hot Jupiter HD 189733 Ab, observed by the TESS mission. It proved to be a good candidate due to its high activity and the presence of spots on its surface (Hazra et al. 2021).

2.3. Transit Model and the `ECLIPSE` Program

`ECLIPSE` is a Python script for modeling stars (with or without spots) and planetary transits (Duque Estrada et al. 2025). The main Model features are: planets, moons, faculae, and spots, allowing for the analysis and study of their impacts on the transit.

MCMC and parallel programming

We integrated parallel C code (open.mp) into our Python scripts to optimize the generation of stellar and planetary matrices, especially during sampling with MCMC. This approach significantly reduced computational time by transferring intensive tasks to compiled and multithreaded C functions. As a result, we observed a speed-up of 50x to 80x, significantly improving simulation efficiency (Pinho, Duque Estrada & Valio 2022).

3. Data

`ECLIPSE` uses the LightKurve library to import telescope data from the Kepler, K2, and TESS missions. This project uses data from the TESS mission and generates the star and planet model, producing a light curve that is compared to the light curve downloaded from the telescope (Figure 2) using the lightkurve.py library. The model incorporates the parameters of the star HD 189733 A and the planet HD 189733 Ab, obtained from The Extrasolar Planets Encyclopaedia (2025).

Fitting Star and Exoplanet Parameters

After the MCMC algorithm fitted the model's light curve (orange curve), we obtained a light curve closer to that downloaded directly from the Kepler telescope (blue curve) (Figure 3).

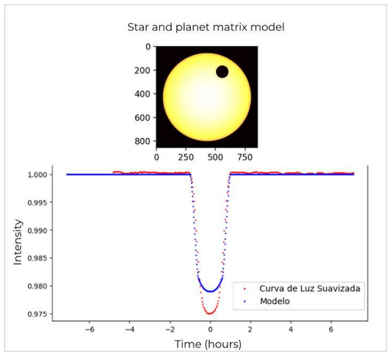

Figure 2. Comparison of the lightcurve of HD189733 A (Kepler data in red, model data in blue).

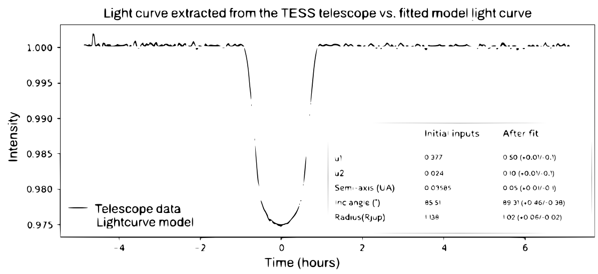

Figure 3. Light curve resulting from adjusting the planet and star parameters (blue curve), compared with the curve downloaded from the telescope (red curve). The right panel in the figure shows the values before and after the data fit.

4. Conclusions and next steps

With the developed `ECLIPSE` script, it was possible to model the HD 189733 A/b system and simulate its transit light curve for comparison with observational data from the TESS telescope. The script uses the MCMC algorithm to precisely fit stellar and planetary parameters, also determining their respective uncertainties. Additionally, the model supports the inclusion of stellar spots and faculae, and its performance **was optimized up to 80x** by integration with parallel computing in C, allowing for more efficient (time) analyses. The developed method is extensible to other planetary systems, contributing to the characterization of exoplanets, and will be applied in the future **to ultraviolet (UV) observations** to improve the detection of active regions through the modeling of Coronal Mass Ejections (CMEs).

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