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Observations of planetary transits carried out at the Observatório do Pico dos Dias (OPD)

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Abstract. With the increasing number of recently detected exoplanets, with more than 3800 objects detected so far, the need for characterization of the physical parameters of these objects emerges. The monitoring of planetary transits has been shown to be an efficient method for the characterization of exoplanets. Transit planets allow measurements of the radius and the planetary mass, providing data on the physical structure of these objects. In this way, the parameters obtained from transit measurements become fundamental for a comparative study between exoplanets of different planetary systems. The use of Bayesian statistics appears as an important tool to determine more accurately the physical parameters of transiting exoplanets. In this work, we will present some preliminary results obtained from the monitoring of transit events, from the newly discovered exoplanets WASP-67b and HATS-24b, where we performed photometric measurements at the Pico dos Dias Observatory. We analyze the light curves using Bayesian inference for the precise determination of the orbital parameters of these exoplanets. In addition to obtaining a better characterization of the physical parameters, our goal is to provide a tool that simultaneously fit light curves, through a package developed in Python language, and that implements MCMC and Bayesian statistical analysis.

Resumo. Com o crescente número de exoplanetas detectados recentemente, sendo mais de 3800 objetos detectados atualmente, aparece a necessidade da caracterização dos parâmetros físicos desses objetos. O acompanhamento de trânsitos planetários tem se mostrado um método eficiente para a caracterização de exoplanetas. Os planetas que apresentam trânsitos permitem medidas do raio e da massa planetária, fornecendo dados da estrutura física destes objetos. Dessa forma, os parâmetros obtidos com as medidas de trânsito tornam-se fundamentais para realização de um estudo comparativo entre exoplanetas de sistemas planetários distintos. O uso de estatística Bayesiana na estimativa dos parâmetros obtidos com essa técnica mostra-se como uma ferramenta importante para estimar, de modo mais preciso, os parâmetros físicos dos modelos de trânsitos planetários. Neste trabalho, vamos apresentar alguns resultados preliminares obtidos do acompanhamento de eventos de trânsitos, dos exoplanetas recém descobertos WASP-67b e HATS-24b, através de medidas fotométricas realizadas no Observatório do Pico dos Dias. Onde pretende-se utilizar a inferência de estatística Bayesiana para a determinação precisa dos parâmetros orbitais desses exoplanetas ao analisar as curvas de luz através. Dessa forma, além de obter uma melhor caracterização dos parâmetros físicos, ao final desse trabalho, objetiva-se disponibilizar uma ferramenta que faça o ajuste simultâneo de curvas de luz, através de um pacote desenvolvido em linguagem Python, e que implementa uma análise com MCMC e estatística Bayesiana.

Keywords. Planets and satellites: fundamental parameters – Planets and satellites: detection – Techniques: photometric

1. Introduction

Currently the number of exoplanets detected exceeds the value of 3800, so it appears the need to characterize the physical parameters of these objects through the monitoring of them. The planetary transit method has proved to be efficient for the study of exoplanets, since about 3000 of these planets present events of planetary transits according to the NASA Exoplanet Archive catalog [1] (Akeson et al. 2013).

Transits of exoplanets are events that occur when a planet passes in front of the disk of its host star, decreasing the flux of the star to a particular observer. By observing these events it is possible to obtain some parameters of the exoplanet such as ray and orbital period. In addition, the parameters obtained with the transit measures become fundamental for conducting a comparative study among exoplanets of different planetary systems.

The use of Bayesian statistics in the estimation of the parameters obtained with this technique is an important tool to estimate with more precision the physical parameters of the transient planetary model (Ford & Gregory 2007). In this study, we attempted to carry out new measurements of the transits for recently discovered WASP-67b and HATS-24b planets, with the goal of increasing the reliability of the parameters that can be estimated with this technique and implementing the use of statistics Bayesian for estimation of the parameters.

These targets were chosen due to the small number of studies of the transits found in the literature for these objects, and also due to some characteristics such as the duration of the transit, which is relatively short, thus allowing a follow-up of the whole event, contributing to a higher quality in the obtaining the data. In this way, we intend to contribute to a better characterization of these systems obtaining new measures for the transits of these objects.

2. Main Goals

In this work we intend to present preliminary results of a project of scientific initiation developed in the Laboratório Nacional de Astrofísica (LNA), which consisted in the observation of transits of recently detected exoplanets for precise determination of the physical parameters of these objects. The objects of our sample have few measurements of their transits in the literature, requiring additional observations for better determination of physical parameters. In addition to the characterization of these exoplanets, it is also possible to find variations in the central time of tran-

[1] https://exoplanetarchive.ipac.caltech.edu/

sit, which may indicate the presence of other bodies in the system or variability due to the presence of starspots. This project also aims to characterize the photometric accuracy of the new CCDs of the SPARC4 instrument (Rodrigues et al. 2012).

3. Methodology

In this work, we initially adapted the pipeline developed by Martioli, et al. (2018), used for the study of eclipses. It is necessary to make modifications this pipeline to use with events of primary transits. The pipeline, written in Python language, uses the BATMAN-BAsic Transit Model cAlculatioN package developed by Kreidberg (2015), which implements the geometric model of Mandel & Agol (2002) for the calculation of light curves. To estimate the posterior probability of the model parameters and the fit curve coefficients, the pipeline uses Bayesian inference when implementing the EMCEE (Foreman-Mackey et al. 2013) package. This package is able to generate samples based on a priori information of the physical parameters together with the data obtained. The EMCEE package uses the Markov chain Monte Carlo set sampler (MCMC) proposed by Goodman & Weare (2010).

For the observations we made a request for time for the OPD, and we managed two nights to carry out our study with the 1.6m aperture telescope, using the Ixon 888 CCD of the SPARC4 project, with the I filter and focal reducer. This arrangement favored the presence of several comparison stars in the field, because, with the focal reducer it was possible to obtain a field of 6.15 x 6.15 (in minutes of arc).

However, we have successfully observed only the transit of the HATS-24b exoplanet completely and under photometric conditions. Already during the observation of the transit of the Wasp-67 we had technical problems with the telescope and also the climatic conditions did not allow to follow the transit event completely. In this way, we will present the analyzes and the results only for HATS-24b.

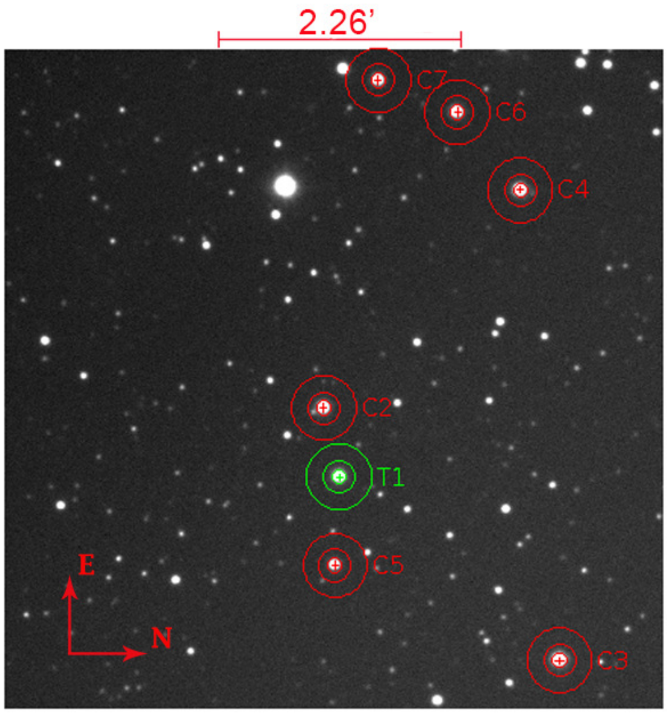

Figure 1: Shows the target HATS-24 demarcated by T1 (in green), and the 6 comparison stars (in red), demarcated by Cn where n = 2, .., 7. We also have the openings for the extraction of the flux.

4. Preliminary Results

Regarding the observations of the transtit of HATS-24b, we were able to get a good sample before and after the passage of the planet through the stellar disk. In the Table 1, we have a summary of the existing observations in the literature for HATS-24b, where we can notice that our experimental arrangement obtained a better precision than the others.

We used AstroImageJ[2] (AIJ) software to perform differential photometry with multiple openings. The AIJ also allows the analysis of light curves, but this was done through a pipeline developed by us. This pipeline is capable of simultaneously generating models for the light curves of the target and for the comparison stars. In addition, our pipeline is able to implement Bayesian statistical inference to perform the estimation of the physical parameters of planetary transient models.Thus, six comparison stars were selected using stars with amplitude of ±1.0 magnitudes close to the target (Figure 1). During photometry, we used the Multi-Aperture (MA) of the AIJ that recalculates the centroid of the target and comparison stars in each image of the time series.

In Table 2, we have the parameters taken from Bento et al. (2017), which were used as a priori information for the HATS-24b exoplanet transit model. Where we use a normal probability distribution for the parameters: central time of transit (T_c), orbital period (P), planet-to-star radius ($R_p/R_\star$), semi-major axis ($a_p/R_\star$), orbital inclination (i), and limb darkening coefficients (u_1 and u_2), where we assume a quadratic limb darkening (Kreidberg 2015). The following parameters are fixed as constant values: eccentricity ($e = 0$) and longitude of periastron ($\omega = 90°$)

We use a priori information along with our data to generate a model with Bayesian inference for the target and also for comparison stars. Where, we apply our analysis simultaneously to all selected stars to the transit model and the background by a quadratic polynomial.

Figure 2 presents the light curves obtained from the differential photometry of the exoplanet HATS-24b in relation to the comparison stars used in the final adjustment. Figure 2 also presents the fit models include the trend models and the global transit model.

Figure 3 presents the final result for this analysis, where we present the reduced light curve of HATS-24b generated through BATMAN, having input values 2. In red, we have the final model for the transit of the target where we remove the trends of the data. The green dots represent the binary data, being a total of 60 bins. Figure 3 in the bottom of presents the residues.

5. Final Considerations

For a preliminary analysis, we performed 100 interactions through the MCMC to determine the posterior probability distribution of each of the variable parameters, where the initial 40 burn-in interactions were discarded. At the end of the analysis the pipeline returns the parameters of the transit model as well as its uncertainties. The final values for each parameter are presented in the Table 2. As a preliminary analysis, the parameters presented are not yet the most accurate for the HATS-24b exoplanet, however it is possible to notice that, in some parameters, a better precision was obtained, for example, the planet radius

[2] http://www.astro.louisville.edu/software/astroimagej/

Table 1: Observações HATS-24b

Observatory	Date	N images	Cadence (sec)	Filter	Depth (mmag)	Reference
LCOGT 1 m+SAAO	2015 Jun 07	90	151	i	18.70 ± 0.86	Bento et al
Rarotonga Observatory	2016 Aug 08	111	69	C	17.3 ± 1.9	Phil Evans
OPD	2017 Jul 14	806	16	I	17.31 ± 0.07	This Work

Table 2: Priors obtained from Bento et al. (2017) and final fit parameters.

Parameter	Prior Type	Initial guess	Final Fit Value	Unit
T_c	Normal	2457948.708 ± 0.010	2457948.7037 ± 0.0001	BJD
P	Normal	1.3484954 ± 1.3e-06	1.3484992± 5.8e-06	days
$R_p/R_\star$	Normal	0.1307 ± 0.003	0.1304 ± 0.0002	-
$a_p/R_\star$	Normal	4.67 ± 0.1	4.6699 ± 0.0001	-
i	Normal	86.6 ± 1.2	86.6 ± 1.2	degrees
e	Fixed	0.	0.	degrees
ω	Fixed	90.	90.	degrees
u_1	Normal	0.1919 ± 0.0100	0.1920 ± 0.0001	-
u_2	Normal	0.3654 ± 0.0100	0.3655 ± 0.0001	-

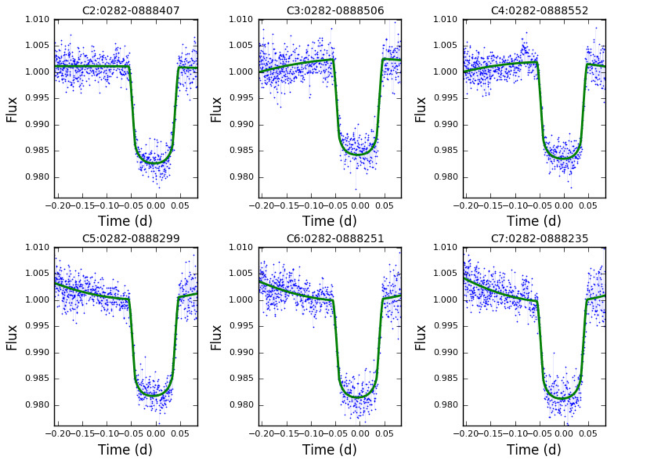

FIGURE 2: This painel shows the models for the comparison stars: C2, C3, C4, C5, C6 and C7. The model is defined by the solid line of green color.

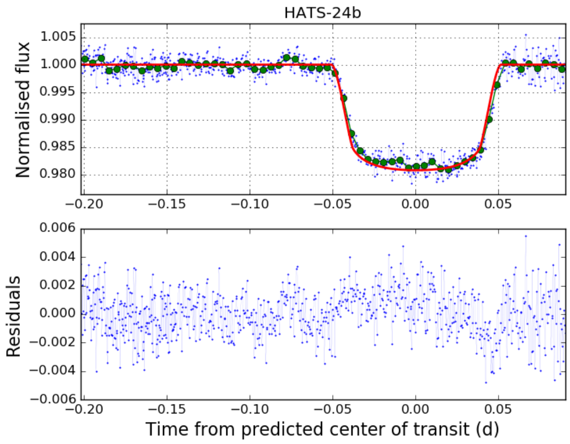

FIGURE 3: Top panel presents the reduced light curve of HATS-24 in blue dots and the binned data (green circles). The fit transit model (red line. The bottom panel shows the residuals.

and the semi-axis major. In a future work, we intend to perform a more robust analysis with a greater number of interactions. In addition, to obtaining the parameters derived from the exoplanet HATS-24b by combining the values obtained by the transit with the stellar parameters of the HATS-24 obtained by the differential analysis using solar spectra as comparison (Meléndez et al. 2009; Ramírez et al. 2014; Tucci Maia et al. 2014, 2016).

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