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Transit modeling of WASP-43b

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Abstract. The goal of this project was to learn how to estimate basic properties of a transiting exoplanet from ground-based transit photometry. We analysed a photometric time series of a single WASP-43b transit. Data reduction was carried out using a custom-built aperture photometry pipeline written in Python, while a custom light-curve modelling code based on `PyTransit` was used for parameter estimation. We obtained a transit time centre $T_0 = 2\,458\,168.0862 \pm 0.0001$, a radius ratio $R_p/R_\star = 0.121 \pm 0.004$ and an impact parameter $b = 0.71 \pm 0.06$. We compared our results with literature and found agreement within 3σ for almost parameters. The two exceptions were the time of the transit centre, T_0, and the radius ratio, both with significant discrepancy. We believe the T_0 discrepancy is due to the bad accuracy of the period and/or T_0 values, while the radius ratio discrepancy could be due to systematics that were not accounted sufficiently by the linear baseline model used in the transit modelling.

Key words: Extrasolar planets – photometry – exoplanet transits – Bayesian statistics

1. Introduction

Since the discovery of the first planet orbiting a solar-like star (Mayor & Queloz, 1995), the study of exoplanets has become one of the most dynamic research fields in astronomy. With the number of exoplanet detections dramatically increasing in recent years, the field is moving from simple detection and statistical studies to the characterization of individual planets.

The transit method is one of the most powerful means to detect exoplanets and it is based on transits caused by the periodic passage of a planet in front of its host star. Modelling transits provide us with a wealth of precious information on the planet, as explained by Winn (2010).

In this paper we describe our analysis step by step: from the reduction of raw data and the normalisation of stellar light curve (**Data**) to the proper analysis and Bayesian statistics (**Transit Fitting**), it will be possible to understand how we extracted transit parameters of WASP-43b (**Conclusions**).

1.1. WASP-43

The set of data belongs to WASP-43, a star located in the Sextans constellation at 80 pc from the Earth. It is a K7V-type star with V=11 as apparent magnitude in GRP GAIA filter and it hosts a hot Jupiter companion (WASP-43b) far 0.01 AU, with a period of 0.8 days (Hellier et al., 2011). The high brightness, the low level of stellar activity and no presence of other planets made this target perfect to learn the basics of transit analysis.

2. Data

Our dataset was collected on the 18th February, 2018. Observations lasted almost 3 hours and images were acquired with MuSCAT2, an imaging instrument installed in Carlos Sánchez Telescope (TCS) at Teide Observatory, Tenerife, Spain. The sensor covers 0.435" per pixel with a total FoV of 7.43 x 7.43 arcmins. It is equipped with a *griz* filter set (4 filters in total). Only the g filter was used for WASP-43 observations, more than 90% of transmission between 410 and 520 nanometers (IAC, 2019). The dataset consisted of 393 FITS images observed in *g'* passband, 328 of them were time-frames of the target, 50 flat-field frames and 15 bias frames. In order to obtain the light curve and extract planet parameters, it was necessary to carry out a reduction of the raw data because of non-uniform illumination and pixel-to-pixel sensitivity variations. We removed these effects in each time-frame by subtracting the Master Bias[1] and dividing by the Master Flat[2] (previously normalised to one).

2.1. Aperture photometry and differential photometry

The aim of the first part of our project was to obtain a light curve from photometric observations. In order to sum up the star's flux and correct it for background contribution, we made aperture photometry. We selected 2 companion stars similar in brightness and shape to our target, as shown in Figure 1. The similar shape allowed us to take the same aperture radius and annulus radius for all of them ($R_{\rm ap}$ = 10 pixels, $R_{\rm an}$ = 20 pixels) using the Python package `photutils`. *Companion 1* is an early G-type star (V=14 mag), while *companion 2* is a late F-type (V=11 mag). They were observed both by GAIA and magnitudes were measured with the GRP GAIA filter. In order to remove light contamination, we subtracted the background ($F_{\rm an}$) from stellar fluxes ($F_{\rm ap}$) in each time-frame. Afterwards, we removed atmospheric systematics and improved the signal-to-noise ratio by performing differential photometry (Winn, 2010), we normalised the flux of our target using the mean of the flux of *companion 1* and *companion 2*. The obtained light curve showed only one transit as reported in Figure 2, where the model is overlapped.

[1]The median of bias frames.

[2]The median of flat-field frames.

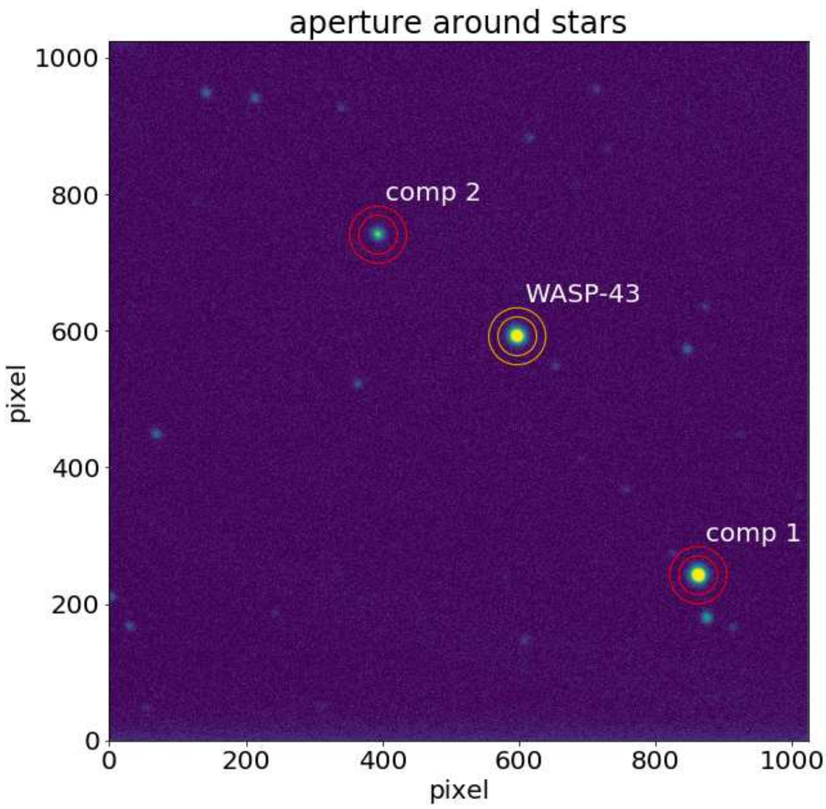

Figure 1. *FoV of WASP-43.* Two stars (companion 1 and 2) were selected to carry out aperture and differential photometry. We chose an aperture radius equal to $R_{ap} = 10$ pixels and an annulus radius equal to $R_{an} = 20$ pixels.

3. Transit fitting

In the second part of the project, we extracted stellar and planetary parameters exploiting Bayesian analysis implemented by the Python software routine `PyTransit` (Parviainen, 2015). A detailed treatment of Bayesian methods could be find in Parviainen (2018). We fitted 8 parameters: baseline slope and intercept, limb darkening coefficients, stellar density, impact parameter, radius ratio and period[3]. We carried out a preliminary analysis using Differential Evolution Algorithm (DEA) in order to obtain an initial set of parameters. They were used as priors for the subsequent MCMC-running in order to get reason-

[3]Our dataset showed only one transit which does not allow to estimate the period. We put an informative prior (P = $0.81347753 \pm 0.00000071$) on it using a literature value only because it was a requirement of the fitting routine.

able posterior distributions. We used 30 chains of 500 iterations to sample the posterior probability distribution. Results are summarised in Table 1.

Table 1. WASP-43b transit analysis results. [*Comment*: parameterisation in sampling space follows Kipping (2013), where the quadratic limb darkening coefficients u and v are mapped from sampling parameters q_1 and q_1. Notation $\mathcal{U}(a, b)$ denotes uniform distribution over interval $[a, b]$, while $\mathcal{N}(\mu, \sigma)$ normal distribution with mean equals μ, and standard deviation σ].

Name	Unit	Prior	Obtained value	Literature value
Transit centre time	MJD	$\mathcal{N}(0, 0.1)$	2458168.0862 ± 0.0001	2458168.6029 ± 0.0030
Stellar density	g cm^{-3}	$\mathcal{U}(0.1, 25)$	2.5 ± 0.4	2.410 ± 0.079
Radius ratio		$\mathcal{U}(0.05, 0.25)$	0.121 ± 0.004	0.1595 ± 0.0008
Impact parameter		$\mathcal{U}(0, 1)$	0.71 ± 0.06	0.656 ± 0.010
Limb darkening u		see comment	1.0 ± 0.3	0.983 ± 0.050
Limb darkening v		see comment	-0.2 ± 0.3	0.065 ± 0.060
Nuisance parameters				
Error logarithm		$\mathcal{U}(-4, 0)$	-3.041 ± 0.017	
Baseline slope s		$\mathcal{N}(0, 0.1)$	-0.0095 ± 0.0015	
Baseline intercept		$\mathcal{N}(1, 0.1)$	1.0010 ± 0.0001	

Results show that almost all parameters are compatible within 3σ with the literature values (Gillon, M. et al., 2012), except for the T_0 and the radius ratio. The discrepancy between values of T_0 could be ascribable both to a bad accuracy of the period and/or T_0. A full O-C analysis could confirm our hypothesis, but unfortunately it was out of scope of the project.

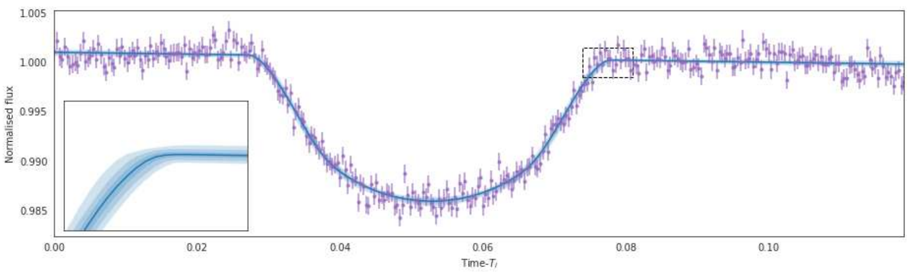

Figure 2. Transit of WASP-43b, centred to T_0. Data coming from Carlos Sánchez Telescope are shown in purple, while the best fit model in blue. The lower right-hand corner shows the zoomed part with median-centred 68%, 95%, and 99.7% central posterior intervals. T_i is the initial time point in our sequence in BJD (2458168.033).

4. Conclusions

The goal of the project was to learn how to estimate exoplanet transit parameters from ground-based photometric observations. We analysed WASP-43b dataset. After removing instrumental effects, we carried out aperture photometry and differential photometry in order to sum up the light of selected stars, subtract the background flux and obtain the stellar light-curve. We subsequently extracted the main planet parameters by exploiting Bayesian analysis and MCMC simulations implemented in `PyTransit`. We obtained results shown in Table 1. We compared our results with those present in literature and we found a good match ($< 3\sigma$) for almost all parameters, while there was a significant discrepancy for T_0 and radius ratio (more than 5σ). We believe the T_0 discrepancy is imputable to a bad accuracy in the period and/or in the predicted T_0, while the difference in radius ratio values could be due to strong systematics generated by the linear baseline model fitting. Future perspectives could be to carry out a full O-C analysis and to use non-linear baseline model fitting in order to unveil the causes of T_0 inaccuracy and avoid systematics in radius ratio deduction, respectively.

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