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Possible evidence of short-period TTV on WASP-4b transit revealed by TESS

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Abstract.
When a star hosts two planets with only one of them showing transit to an external observer, the gravitational interaction among the planets and its parent star causes advances and delays in the measured transit times when compared to the scenario where only the transiting planet exists in the system. These variations are called Transit Timing Variations (TTVs). In this work, we used 29 transits of the exoplanet WASP-4b observed by TESS to measure the mid-transit times and fit a linear ephemeris to them. Analyzing the residuals from the fit, we found a possible evidence of short-period TTVs with an amplitude smaller than 2 min. However, due to the uncertainties in the mid-transit times are the same order as the amplitude of the TTV singal, we were unable to obtain conclusive results on what causes these variations.

Resumo. Quando uma estrela hospeda dois planetas com apenas um deles mostrando trânsito para um observador externo, a interação gravitacional entre os planetas e sua estrela-mãe causa avanços e atrasos nos tempos de trânsito medidos quando comparados ao cenário em que apenas o planeta em trânsito existe no sistema. Essas variações são chamadas de Variações de Tempo de Trânsito (TTVs). Neste trabalho, usamos 29 trânsitos do exoplaneta WASP-4b observados pelo TESS para medir os tempos de trânsito médio e ajustar uma efeméride linear a eles. Analisando os resíduos do ajuste, encontramos uma possível evidência de TTVs de curto período com uma amplitude menor que 2 min. No entanto, devido às incertezas nos tempos de trânsito médio serem da mesma ordem que a amplitude do sinal de TTV, não conseguimos obter resultados conclusivos sobre o que causa essas variações.

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

1. Introduction

The detection of the first extrasolar planet around a main sequence star by Mayor & Queloz (1995) was the first evidence of the existence of giant gaseous planets in extreme close orbits, known as hot Jupiters. These exoplanets are easier to be detected due to a combination of its proximity to the host star, short orbital periods (namely, $a < 0.1$ AU and $P_{\rm orb} < 10$ days, respectively), and size (that are comparable to Jupiter). Since this discovery, more than 5780 exoplanets were discovered according to the *NASA Exoplanet Archive*[1], most of them by space missions strongly dedicated to detect exoplanets through transit method, such as Kepler and the Transiting Exoplanet Survey Satellite (TESS; Ricker et al. 2015), with ~ 2770 and ~ 570 exoplanets discovered, respectively.

In multiplanetary systems, some of the exoplanets may not be directly detectable by transit. However, the presence of a non-transiting exoplanet in the system, gravitationally perturbs the orbit of its transiting companion, producing advances or delays in the mid-transiting times of the latter. Examine those variations and characterize those non-transiting exoplanets is in the core of the Transit Timing Variation (hereafter, TTV) technique (see e.g., Agol et al. 2005; Nesvorný & Morbidelli 2008; Lithwick, Xie & Wu 2012; Deck & Agol 2015; Agol & Deck 2016; Agol & Fabrycky 2017). One of the advantages of this technique is that it is not only able to detect non-transiting exoplanets, but also provide a good estimative of its mass, independently of radial velocity measurements (e.g., Nesvorný & Morbidelli 2008; Lithwick, Xie & Wu 2012; Deck & Agol 2015). Up to date, 32 exoplanets were discovered by this technique.

In this contribution, we present a possible evidence of a short-period TTV signal on TESS data of WASP-4b, a 1.2 $M_{\rm J}$ hot Jupiter first identified by Wilson et al. (2008), that orbits its host star each 1.338 days. In Sect. 2 we present how the TESS data was selected and in Sect. 3 we show how WASP-4b transits were fitted to obtain mid-transit times and the resulting $O - C$. The discussion about our results is presented in Sect. 4 and our conclusions are shown in Sect. 5.

2. Data selection

WASP-4 is in the TESS southern viewing zone and was observed with a 2 min cadence during sectors 2 (from August 23, 2018 to September 20, 2018) and 69 (from August 25, 2023 to September 20, 2023), and 20 s cadence during sectors 28 (from July 31, 2020 to August 25, 2020) and 29 (from August 26, 2020 to September 21, 2020). For our work, we use only the data from the consecutive sectors 28 and 29, in order to achieve the most continuous coverage of WASP-4b transits to better characterize short period TTVs.

We retrieve the light-curve files directly from the Barbara A. Mikulski Archive for Space Telescopes (MAST[2]). To avoid instrumental systematic artifacts, we used the Presearch Data Conditioning Simple Aperture Photometry (PDCSAP) light curves produced by the TESS Science Processing Operations Center (SPOC; Jenkins et al. 2016) pipeline. These light curves

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

[2] https://archive.stsci.edu/

contains a total of 29 transits of WASP-4b and are shown in Fig. 1.

3. Data analysis

Once the light curves from sectors 28 and 29 were retrieved, we started to fit each transit individually. To model the transit signal we used the `batman` python package (Kreidberg 2015) together with a Markov Chain Monte Carlo (MCMC) method, implemented through the `emcee` package (Foreman-Mackey et al. 2013). We consider as free parameters the mid-transit time ($T_{\rm mid}$), the planet-to-star radius ratio ($R_p/R_\star$), the semi-major axis normalized to the stellar radius ($a_p/a_\star$) and the orbital inclination (i_p). All other parameters were taken from Turner et al. (2022) and we keep them fixed during the fitting procedure. We also consider a quadratic limb-darkening, whose coefficients u_1 and u_2 were obtained from Claret (2017) and set to 0.382 and 0.210, respectively.

Table 1. Fitted mid-transit times and cycles for the 29 transits of WASP-4b observed by TESS during sectors 28 and 29.

Cycle	$T_{\rm mid}$ (BJD)
0	$2459063.10876^{+0.00038}_{-0.00037}$
1	$2459064.44756^{+0.00035}_{-0.00036}$
2	$2459065.78501^{+0.00040}_{-0.00040}$
3	$2459067.12423^{+0.00039}_{-0.00037}$
4	$2459068.46157^{+0.00041}_{-0.00041}$
5	$2459069.80004^{+0.00043}_{-0.00045}$
6	$2459071.13840^{+0.00046}_{-0.00044}$
10	$2459076.49106^{+0.00041}_{-0.00045}$
11	$2459077.82928^{+0.00039}_{-0.00041}$
12	$2459079.16775^{+0.00040}_{-0.00040}$
13	$2459080.50612^{+0.00043}_{-0.00046}$
14	$2459081.84442^{+0.00039}_{-0.00037}$
15	$2459083.18184^{+0.00042}_{-0.00038}$
16	$2459084.52047^{+0.00044}_{-0.00040}$
19	$2459088.53494^{+0.00031}_{-0.00034}$
20	$2459089.87362^{+0.00032}_{-0.00032}$
21	$2459091.21182^{+0.00032}_{-0.00032}$
22	$2459092.54982^{+0.00038}_{-0.00039}$
23	$2459093.88759^{+0.00033}_{-0.00033}$
24	$2459095.22607^{+0.00036}_{-0.00033}$
25	$2459096.56471^{+0.00033}_{-0.00033}$
26	$2459097.90259^{+0.00037}_{-0.00036}$
30	$2459103.25534^{+0.00033}_{-0.00034}$
31	$2459104.59403^{+0.00033}_{-0.00032}$
32	$2459105.93248^{+0.00035}_{-0.00033}$
33	$2459107.27102^{+0.00032}_{-0.00033}$
34	$2459108.60891^{+0.00035}_{-0.00033}$
35	$2459109.94692^{+0.00034}_{-0.00037}$
36	$2459111.28503^{+0.00033}_{-0.00034}$

For the MCMC fitting procedure of each transit, we used 10000 steps and 32 walkers (eight times the number of free parameters), assuming uniform priors for each free parameter. At each step of the MCMC procedure, we computed the reduced goodness-of-fit estimation through

$$\chi^2_{\rm red} = \frac{1}{N-M}\sum_{j=1}^{N}\left(\frac{O_j - C_j}{\sigma_j}\right)^2, \qquad (1)$$

where N is the number of observed points, M is the number of free parameters and the term of the sum is the unreduced χ^2. We then discard the first 5000 steps as burn-in and take the median as our results with errors being the 1σ confidence interval (±34%). The results obtained for the mid-transit times of the 29 transits are shown in Tab. 1.

4. Results & Discussion

To obtain the $O-C$ diagram, we first fit a linear ephemeris to the mid-transit times of Wasp-4b derived from sectors 28 and 29 using MCMC with 5 000 steps, 20 walkers and discarding the first 2 000 steps as burn-in. The resulting ephemeris is,

$$T_{\rm mid}({\rm BJD}) = 2459063.10890 \pm 0.00014 + 1.33823 \pm 0.00001 \times E \qquad (2)$$

where $T_{\rm mid}$ is the predicted mid-transit time and E is the cycle. We use this equation to obtain the expected mid-transit times if there is no extra body in the system perturbing it, and subtract these values from those obtained by fitting each transit.

The resulting $O-C$ diagram is shown in Fig. 2. This Figure shows hints of a possible short-period TTV with a small amplitude (less than 2 min in the $O-C$ diagram), specially in the region between cycle 30 and 36. We tried to fit the TTV using the python version of the `TTVFast` code by Deck et al. (2014). However, due to the uncertainties in the mid-transit times determination that are of the same order of TTV amplitude, no conclusive fit could be made and, therefore, the nature of such small variation could not be traced.

5. Conclusion

In this work we analyzed the transits of the exoplanet WASP-4b in sectors 28 and 29 of the TESS data. The 29 transits in those sectors were analyzed and their mid-transit times were obtained. We also derived a linear ephemeris for those mid-transit times and subtracted the observed values from those predicted by this ephemeris. The resulting $O-C$ presents hints of a possible short-period TTV with a small amplitude (less than 2 min). We tried to fit this variation, but the TTV amplitude order uncertainties in the fitted mid-transit times, prevents us to obtain a conclusive solution on which is producing those variations.

More precise and continuous observations of WASP-4b transits are required in order to reduce the uncertainty in the fitted mid-transit times and obtain a conclusive solution for the variation observed in the $O-C$ diagram.

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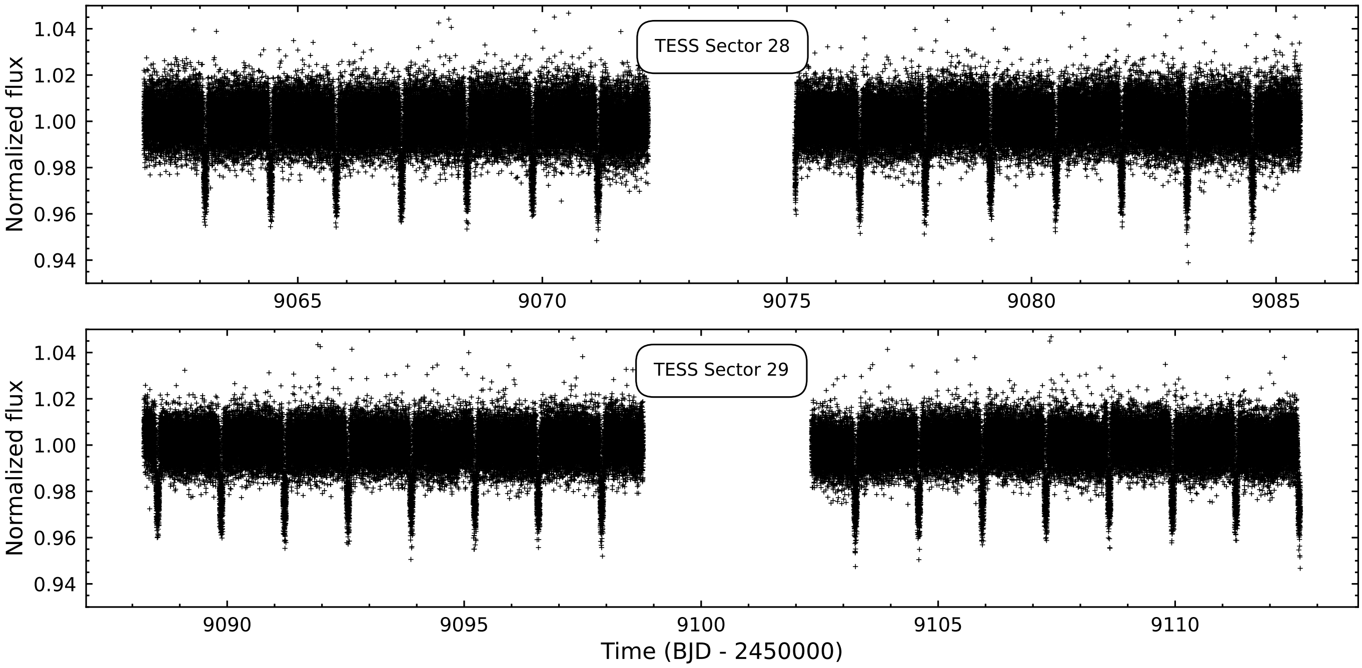

Figure 1. Normalized PDCSAP light curves of WASP-4 from sectors 28 and 29, produced by TESS-SPOC.

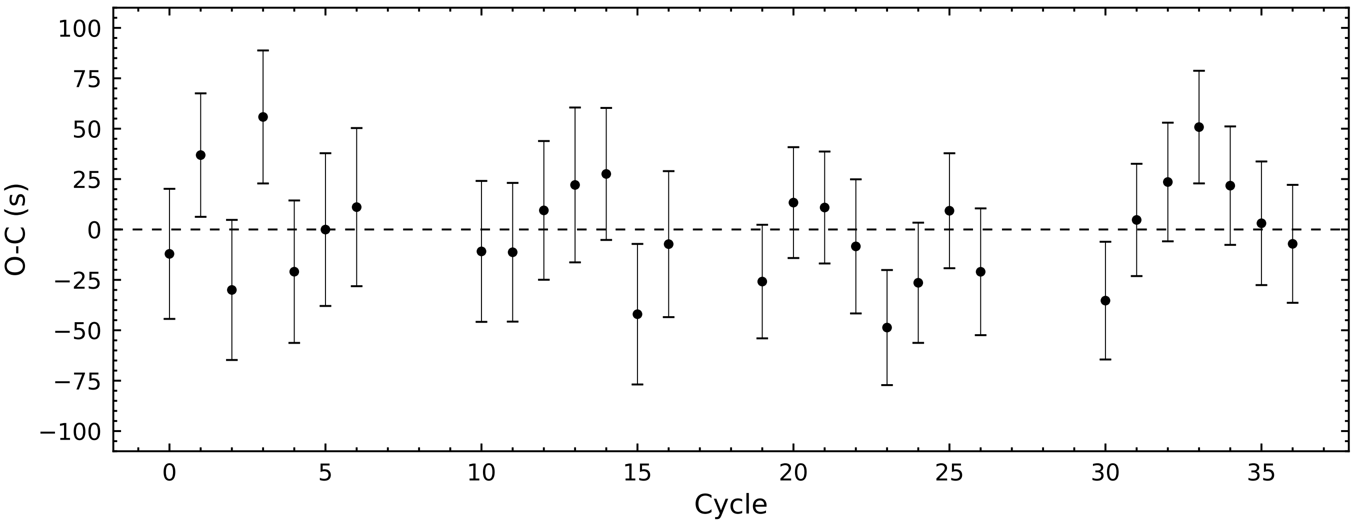

Figure 2. $O - C$ diagram for WASP-4b transits in TESS sectors 28 and 29.

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