XO-7 as a possible multi-object planetary system characterised with TESS and MUSICOS/SP

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Introduction

- XO-7b is a hot Jupiter transiting a $V = 10.52$ mag G0V-type star (Crouzet et al. 2020). The planetary system is interesting because the linear slope (Fig. 1) in the discovery radial-velocity (RV) data indicated a wide-orbit massive companion. In 2020 we started an RV campaign for the system with the main scientific goal to follow-up this linear slope, and to put constraints on the orbital period of the companion.
- Furthermore, we aimed at refining the system parameters and we wanted to probe transit time variations (TTVs) of XO-7b in order to search for long-term dynamical signs of the companion of XO-7b in the observed-minus-calculated (O-C) data of mid-transit times.
- To fulfill these aims we analysed the 2-min integrated TESS (Ricker et al. 2014, 2015) PDCSAP data from 8 sectors and performed a long-term RV monitoring of the planetary system using the fiber-fed echelle spectrograph of MUSICOS design (Baudrand & Bohm 1992), installed on the 1.3m telescope of the Skalnaté Pleso (SP) Observatory in Slovakia. Moreover, in our analysis, we also used the discovery RVs, obtained with the SOPHIE spectrograph (Perruchot et al. 2008).

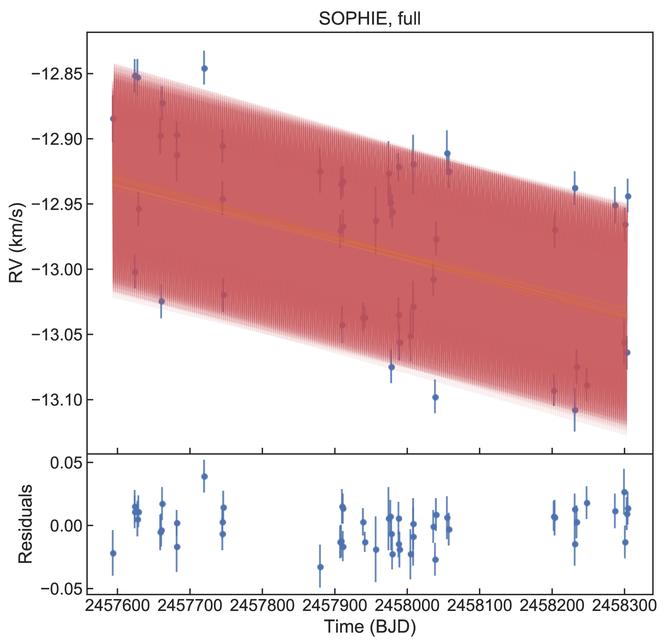

Fig. 1. SOPHIE RV observations of XO-7, overplotted with the best-fitting Allesfitter model (20 curves from random posterior samples). Without phase-folding to see the linear slope in the RV data. Residuals are also shown.

Observations and Data Analysis

- To derive new orbital and planetary parameters we employed the Allesfitter software package (Guenther & Daylan 2019, 2021). In order to construct the combined TESS and RV model we opted for the nested sampling fit option with initial settings. To model the TESS flux baseline we applied a Gaussian Process (GP) regression method. The RV baseline was modelled with a linear function motivated by the discoverers, who reported on a linear slope in the discovery RV data with a value of $S_{\rm SOPHIE} = -0.1480 \pm 0.0010$ m s^{-1} d^{-1}.
- The fitted RVs are depicted in Figs. 1 and 2, and the stacked and binned TESS PDCSAP transit light curve of XO-7b, overplotted with the best-fitting Allesfitter model is shown in Fig. 3.

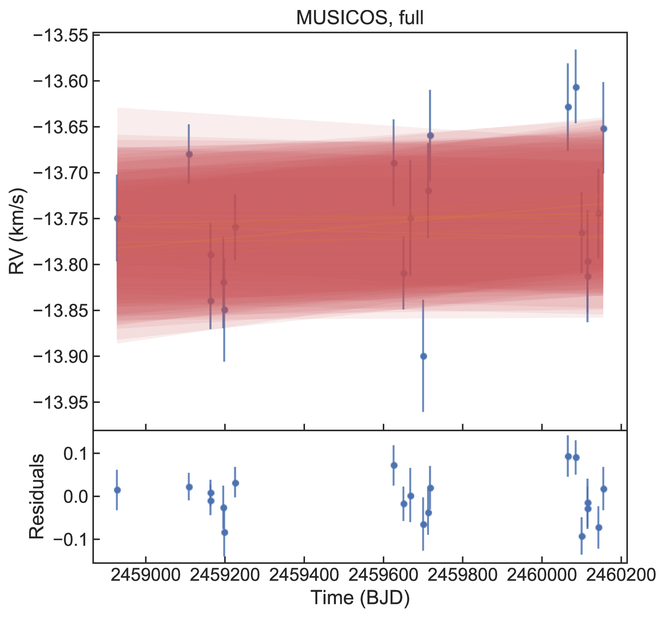

Fig. 2. MUSICOS broadening function (BF) RV observations of XO-7, overplotted with the best-fitting Allesfitter model (20 curves from random posterior samples). Without phase-folding to see the linear slope in the RV data. Residuals are also shown.

Refined system parameters

- XO-7b is a hot Jupiter on a close-in orbit with a short orbital period of $P_{\rm orb} = 2.86413296 \pm 0.00000055$ d. We see its orbit nearly edge-on with an inclination angle of $i = 83.228 \pm 0.098$ deg. XO-7b is an inflated gaseous exoplanet. We obtained a planet-to-star radius ratio, which is $R_{\rm p}/R_{\rm s} = 0.09344 \pm 0.00028$. Using a stellar radius of $R_{\rm s} = 1.480 \pm 0.022$ R$_\odot$ (Crouzet et al. 2020), we can get an absolute planet radius of $R_{\rm p} = 1.346 \pm 0.020$ R$_{\rm Jup}$.
- The mass of the planet was derived based on an RV semi-amplitude, which is $K = 0.0805 \pm 0.0021$ km s^{-1}. This gives $M_{\rm p} = 0.726 \pm 0.038$ M$_{\rm Jup}$. Using a stellar mass of $M_{\rm s} = 1.405 \pm 0.059$ M$_\odot$ (Crouzet et al. 2020), we can get a mass ratio of $q_{\rm m} = 0.000493 \pm 0.000015$ and applying the obtained planet mass and radius parameter values, we can get a planet density of $\rho_{\rm p} = 0.369^{+0.030}_{-0.028}$ g cm^{-3}. This is only about 28.5% of Jupiter's density.

TTV analysis

- The first TTV analysis of XO-7b was performed by the discoverers (Crouzet et al. 2020). Later, Maciejewski (2022) analysed TESS data from three sectors, and found no additional planet in the XO-7 system down to sub-Neptune-sized planets. Since this analysis new TESS data were obtained (Fig. 3), we decided to repeat the TTV analysis with a much longer timebase, which enabled us to focus on long-term dynamical signs of the announced companion of XO-7b.

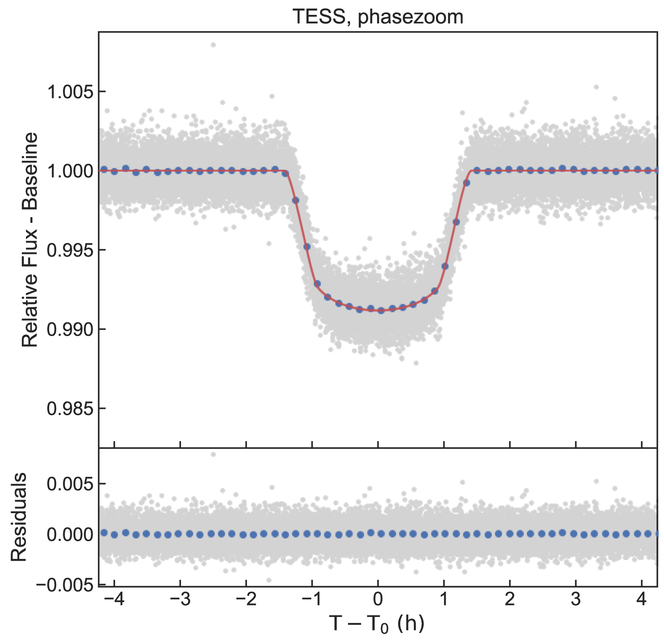

Fig. 3. Stacked and binned TESS transit light curve of XO-7b, overplotted with the best-fitting Allesfitter model (20 curves from random posterior samples). Residuals are also shown.

- We excluded partial transits from the dataset, which means that we used 65 TESS transits of XO-7b in total, covering a timebase of about 977 days. To perform the TTV analysis we again employed the Allesfitter software package. The O-C (TTV) data (Fig. 4) were subsequently inputted in the OCFit code (Gajdoš & Parimucha 2019) and tested for any quadratic trends in the dataset, which could be an indicator of the announced massive wide-orbit companion.

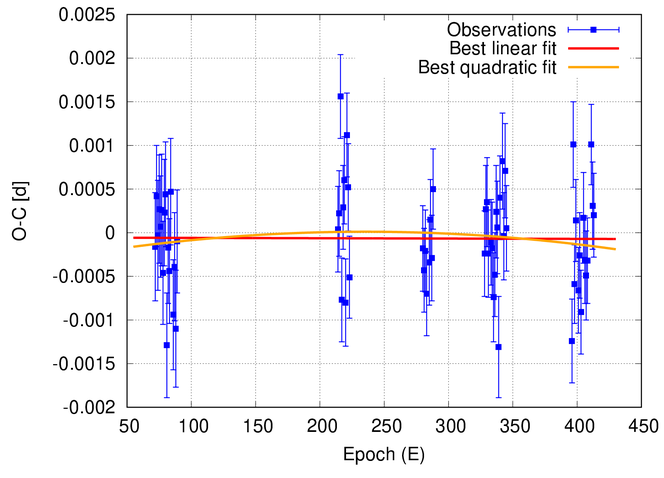

Fig. 4. Observed-minus-calculated (O-C) diagram of XO-7b mid-transit times, obtained based on 2-min integrated TESS PDCSAP data, overplotted with the best-fitting OCFit models.

- We did not find significant evidence of the companion of XO-7b in the O-C dataset of mid-transit times. We can conclude that if the announced companion really exists, this is in agreement with previous results that distant companions of exoplanets are only known by RV solutions.

RV analysis

- Our most interesting result is that the previously observed significant linear slope, $S_{\rm SOPHIE} = -0.1040 \pm 0.0065$ km s^{-1} T$_{\rm obs}^{-1}$ (Fig. 1), in the SOPHIE RVs was not confirmed with the follow-up MUSICOS RV data. We detected only a marginal linear slope, $S_{\rm MUSICOS} = 0.040 \pm 0.029$ km s^{-1} T$_{\rm obs}^{-1}$ (Fig. 2), in the newly obtained RV data, which has the opposite trend compared to the linear slope reported by the discoverers.
- We can conclude that if the announced companion really exists, the most convincing explanation is that both RV datasets were collected near its quadrature position (Fig. 5).

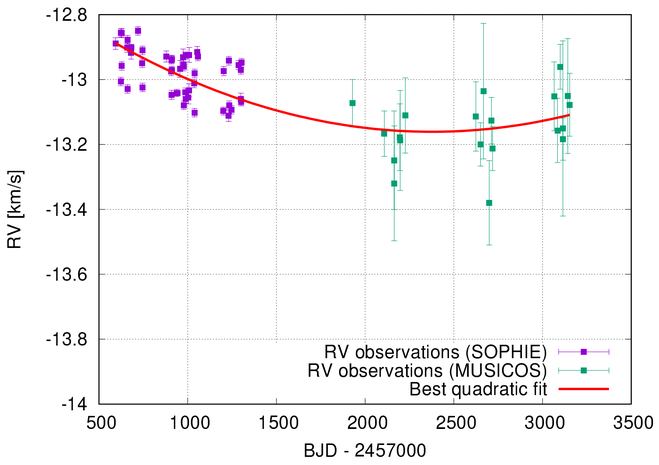

Fig. 5. SOPHIE RV observations and MUSICOS cross-correlation function (CCF) RVs of XO-7, fitted jointly with a quadratic model.

Preliminary parameters of the companion

- We used the quadratic RV solution of the merged SOPHIE and MUSICOS data (Fig. 5) to infer some preliminary physical parameters of the announced companion of XO-7b.
- We calculated the minimum RV semi-amplitude $K_{\rm min,3}$ induced by the companion, as the absolute difference between the minimum and maximum RV values of the quadratic-fit curve during the merged timebase of RV observations divided by two.
- The minimum orbital period $P_{\rm orb,min,3}$ of the announced companion of XO-7b was calculated following Kipping et al. (2011) and Pinamonti et al. (2022) as a function of the quadratic acceleration coefficient q:

$$P_{\rm orb,min,3} \gtrsim 2\pi \sqrt{\frac{2K_{\rm min,3}}{q}},$$

and we obtained 7900 ± 1660 d.

- From $P_{\rm orb,min,3}$ and $K_{\rm min,3}$, the corresponding 'minimum' minimum mass $(M_3 \sin i)_{\rm min}$ of the companion can be derived, e.g. by modifying the formula presented by Torres, Winn & Holman (2008):

$$(M_3 \sin i)_{\rm min} = 4.919 \times 10^{-3}\, K_{\rm min,3}\, (P_{\rm orb,min,3})^{1/3}\, (M_{\rm s})^{2/3},$$

where $K_{\rm min,3}$ is in m s^{-1}, $P_{\rm orb,min,3}$ is in days, $M_{\rm s}$ is in M$_\odot$, and the result is expressed in M$_{\rm Jup}$. We assumed that $M_3 \ll M_{\rm s}$ and that the announced companion has a circular orbit. We obtained a 'minimum' minimum mass of $(M_3 \sin i)_{\rm min} = 16.7 \pm 3.5$ M$_{\rm Jup}$.

Summary

- We obtained precise orbital and planetary parameters of the system via a combination of the TESS data and RV observations of XO-7.
- We did not find significant clues about the companion of XO-7b in the follow-up O-C and RV data. The most convincing explanation is that both RV datasets were collected near its quadrature position.
- The companion of XO-7b, if really exists, could be a brown dwarf or a low-mass star. Compared to the minimum-mass parameter value of 4 M$_{\rm Jup}$, derived by Crouzet et al. (2020), the new value from this work is higher, and within the 1σ uncertainty, it excludes the possibility that the announced companion could have a planetary nature.

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