Rapidly rotating stars and their transiting planets: KELT-17b, KELT-19Ab, and KELT-21b in the CHEOPS and TESS era

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Introduction

- Rapidly rotating early-type main-sequence stars with transiting planets are interesting in many respects. Unfortunately, several astrophysical effects in such systems are not well understood yet. Therefore, we performed a photometric mini-survey of three rapidly rotating stars with transiting planets, namely KELT-17b (Zhou et al. 2016), KELT-19Ab (Siverd et al. 2018), and KELT-21b (Johnson et al. 2018; see Fig. 1), using the *Characterising Exoplanets Satellite* (*CHEOPS*) space observatory, complemented with *Transiting Exoplanet Survey Satellite* (*TESS*) data, and spectroscopic data.
- We aimed at investigating the spin-orbit misalignment and its photometrical signs, therefore the high-quality light curves of the selected objects were tested for transit asymmetry, transit duration variations (TDV), and orbital precession. Furthermore, we performed transit time variation (TTV) analyses, obtained new stellar parameters, and refined the system parameters.

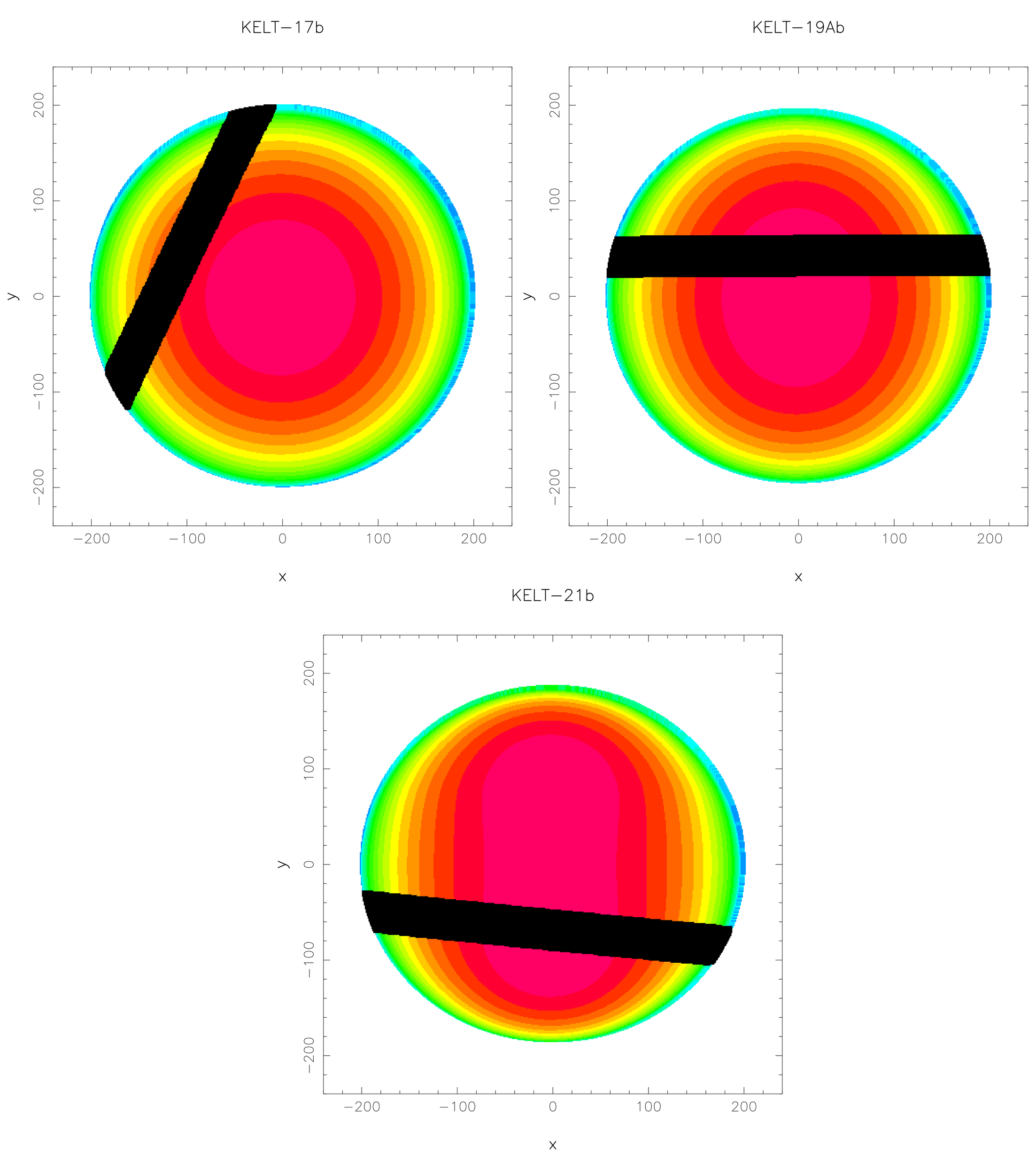

Fig. 1. 2D illustration of the transit chord of KELT-17b, KELT-19Ab, and KELT-21b in front of the stellar surfaces. The green-yellow-red-magenta coloring scheme of the stellar surfaces reflects the apparent surface brightness (intensity). The stellar inclination is always $I_* = 90$ deg.

Observations and Data Analysis

- The transits of KELT-17b, KELT-19Ab, and KELT-21b were observed photometrically using the *CHEOPS* space observatory (Benz et al. 2021). The spectroscopic observations were obtained at the Skalnaté Pleso Observatory (Slovakia), using the 1.3 m f/8.36 Astelco Alt-azimuthal Nasmyth-Cassegrain reflecting telescope, equipped with a fiber-fed echelle spectrograph of MUSICOS design (Baudrand & Bohm 1992). We also used available *TESS* data (Ricker 2014).
- We tried to fit the averaged spectra of KELT-17, KELT-19A, and KELT-21 with several spectral synthesis softwares, but only the `FASMA` code (Tsantaki et al. 2018) led to reasonable results. This could be due to the relatively high temperature of the host stars.
- To derive the system parameters, we used the dedicated *CHEOPS* transit analysis software `pycheops` (Maxted et al. 2021). This `Python` package includes downloading, visualizing, and decorrelating *CHEOPS* data, fitting transits of exoplanets, and calculating light curve noise.
- The *CHEOPS* transit light curves from the viewpoint of spin-orbit misalignment were analyzed using the `RMF` code. This software was already used with success, e.g., in Szabó et al. (2020), where the spin-orbit misaligned Kepler-13A system was re-analyzed using *Kepler* and *TESS* data.
- We compared the transit durations of the exoplanets coming from up to three seasons of observation (*CHEOPS*, *TESS*, and literature data), which is enough to uncover possible long-term TDVs – signs of orbital precession. Simultaneously, we also checked the orbit inclination angle values, because the possible orbital precession should be visible in this parameter, as well (Szabó et al. 2012, 2020).
- To uncover possible TTVs, which can indicate additional substellar objects, i.e., planets or brown dwarfs in the systems, we constructed observed-minus-calculated (O-C) diagrams for mid-transit times using the `OCFIT` code (Gajdoš & Parimucha 2019). To final check the possibility of additional objects in the systems we fitted the O-C datasets of mid-transit times with linear and quadratic functions.

Results

- Since the high effective temperature and the rapid rotation of the stars, the spectroscopic modeling was challenging in these cases and the resulting stellar parameters are not so precise as we expected before.
- We improved mainly the projected rotational velocities, derived based on the broadening function technique (Rucinski 1992), see Fig. 2 for an example. For KELT-17 we obtained $v \sin I_* = 48.49 \pm 0.15$ km s^{-1}, in the case of KELT-19A we got $v \sin I_* = 86.36 \pm 0.21$ km s^{-1}, and for KELT-21 we derived $v \sin I_* = 141.9 \pm 2.4$ km s^{-1}.

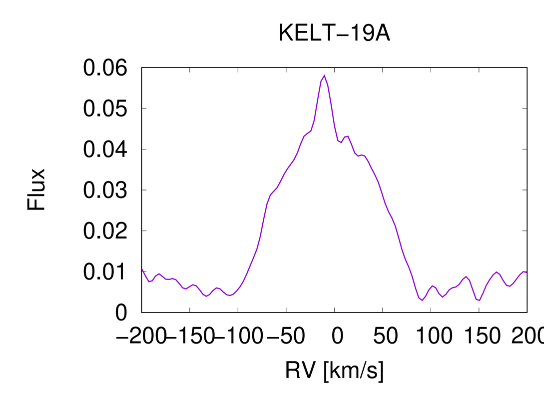

Fig. 2. Selected broadening function of KELT-19A. The radial velocities (RV) are barycentric. The secondary component KELT-19B is well visible as a narrow peak on top of the broad profile of the primary component KELT-19A.

- Based on the *CHEOPS* photometric observations (see Fig. 3) we were able to derive significantly improved system parameters in comparison with the previously published values. Based on these results we can conclude that KELT-17b and KELT-19Ab have smaller planet radius as found before, but in the case of KELT-17b this could be also due to the parameter degeneracy. For KELT-21b we could confirm the previously obtained system and planet parameters within 3σ.

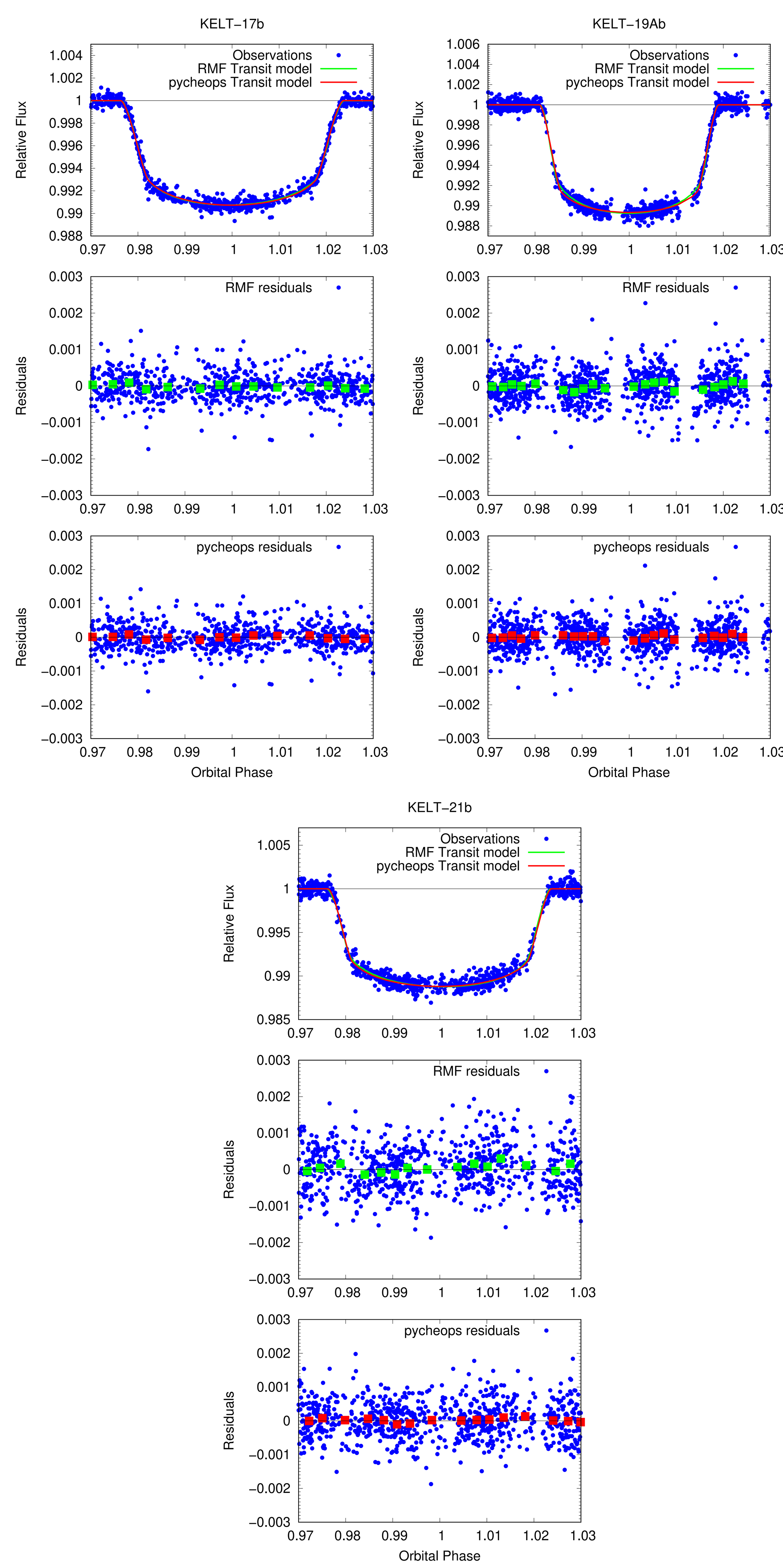

Fig. 3. Phase-folded *CHEOPS* transit light curves of the exoplanets, overplotted with the best-fitting models. The residuals were binned to highlight the possible wave shape (1 bin-point represents 50 data-points).

- The *CHEOPS* light curves were also analyzed from the viewpoint of spin-orbit misalignment. Here we were able to confirm only that the gravity-darkening effect is very low in these cases. The asymmetry is about 0.00005, 0.00001, and 0.00015 in the cases of KELT-17b, KELT-19Ab, and KELT-21b, respectively. *CHEOPS* data are too noisy to draw any conclusions on spin-orbit misalignment from the photometry alone.
- In addition, based on these analyses we can report on a tentative indication that the stellar inclination of KELT-21 is $I_* \approx 60$ deg. We registered the lowest χ^2 at this value, and the quality of the fit decreased both below and above of this inclination angle value. In the cases of the relatively slowly rotating systems of KELT-17 and KELT-19A it does not affect the quality of the fit, thus we could not draw any conclusions for these systems.

- In the case of KELT-19Ab we were able to exclude long-term TDVs causing orbital precession. The shorter transit duration compared to the discovery paper is probably a consequence of a smaller planet radius. KELT-17b and KELT-21b are very similar from this viewpoint – the data are inconclusive, due to parameter uncertainties (see Fig. 4). On the other hand, in these two cases there is an indication that a long-term TDV may exist in a connection with orbital precession, therefore these systems could be interesting from this viewpoint. More data are needed to confirm the orbital precession/long-term TDV.

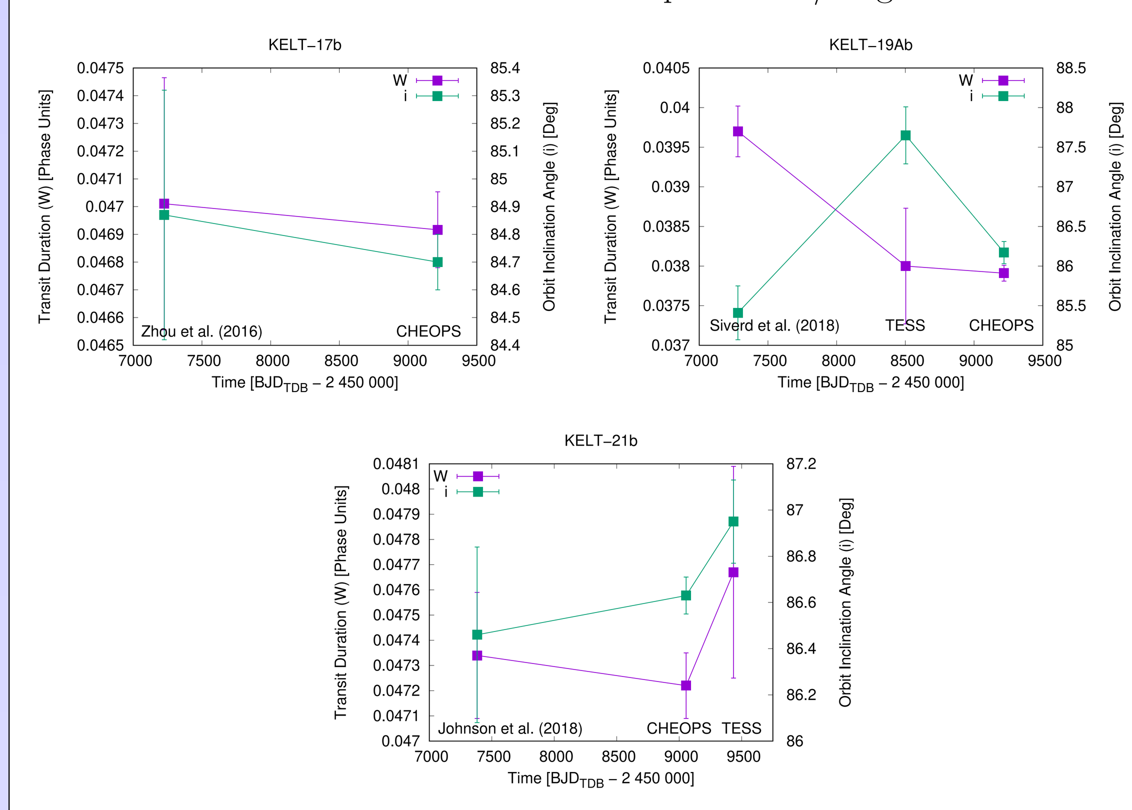

Fig. 4. Transit durations and orbit inclination angles of the exoplanets in different seasons, obtained based on literature data, *CHEOPS*, and *TESS* observations.

- Furthermore, via observed-minus-calculated diagrams of mid-transit times (see Fig. 5) we probed the photometry data from the viewpoint of additional objects in the systems, but we did not find any convincing evidence. Based on the *CHEOPS* and *TESS* observations we set new upper limits on possible TTV semi-amplitudes and we were able to improve further the orbital period of the planets.

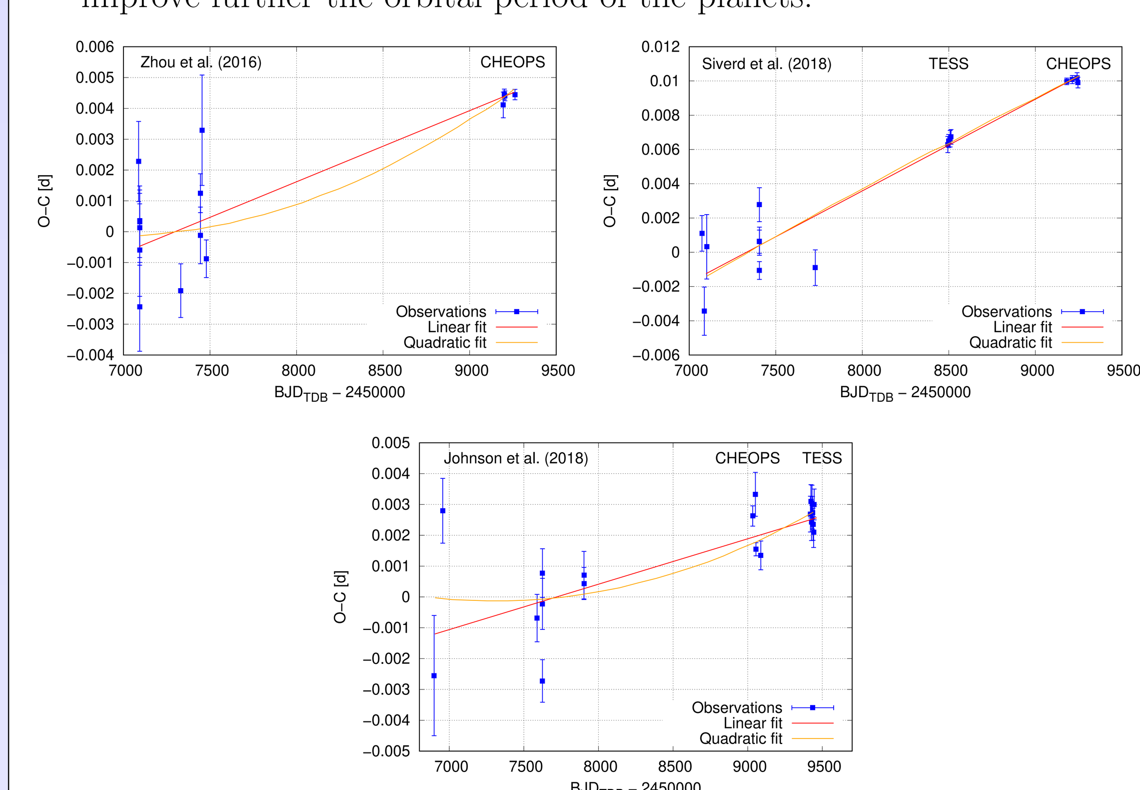

Fig. 5. Observed-minus-calculated (O-C) diagrams of the exoplanets mid-transit times, obtained based on literature data, *CHEOPS*, and *TESS* observations.

Acknowledgements

This work was supported by the Hungarian NKFI grant No. K-119517, by the GINOP No. 2.3.2-15-2016-00003 of the Hungarian National Research, Development and Innovation Office, by the City of Szombathely under agreement No. 67.177-21/2016, by an ESA PRODEX grant under contracting with the ELTE University, and by the VEGA grant of the Slovak Academy of Sciences No. 2/0031/22. TP acknowledges support from the Slovak Research and Development Agency – the contract No. APVV-20-0148. AC acknowledges financial support from the State Agency for Research of the Spanish MCIU through the "Center of Excellence Severo Ochoa" award for the Instituto de Astrophysics of Andalusia (SEV-2017-0709).