NKFIH KH 130372 FINAL REPORT

Search for and Analysis of Peculiar Eclipsing Variable Stars in the Data Set Observed by *TESS* Space Telescope

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We aimed to analyse the expected huge amount of space-borne photometric data of *TESS* spacescraft. We proposed primarily to analyse eclipse timing variations (ETV) data of large sets of eclipsing binaries (EBs) to discover and study dynamically active compact hierarchical triple (CHT), and multiple stellar systems to enhance their sample substantially and, therefore, constrain the formation theories of binary and multiple star systems. In addition, we expected to detect new, peculiar multiple objects in the monthly growing sample of *TESS* data and proposed the analysis of some of these systems.
After the download the data of the first *TESS*-sectors, we realized that it would be worthy to reverse the order of the priority of our research points. The main reason was, that *TESS* spacecraft has discovered much more peculiar multiple stellar systems than it was expected. Therefore, we found that the thorough analysis of such systems – with our novel methods developed in the frame of our previous NKFIH granted research project K-113117 – may offer much more short-term extra scientific benefits and furthermore, for the large competition amongst different groups of researchers, it was important to carry out these investigations as quickly as possible. Moreover, there was another, technical reason for reversing the order of the research points. For the budget of this proposal we purchased a new, high-speed workstation dedicated for the ETV studies of the *TESS* EBs locating both in the continuous viewing zones and in the original *Kepler*-field. This computer, however, seriously damaged shortly after its installation due to a giant storm in the region of Baja Observatory. Finally, we replaced this workstation with a new one during the extended time interval of the project, however, such a manner, the analysis has been delayed significantly. Thus, the main results of the project mostly connected to the analyses of new, peculiar, compact hierarchical triple and multiple stellar systems, as follows:

Results

1) Continuous improvement of our formerly developed software packages for the complex spectro-photodynamical analysis of various, multi-site observations of binary, triple and multiple stellar systems

The main output of our previous, NKFIH/OTKA granted research project (K-113117) was, the new software package, named LIGHTCURVEFACTORY, which now has been used for the complex analyses of several newly discovered *TESS* multiple stars. The variety, and extremity of the numerous new discoveries made it necessary to improve the code continuously, building in new features into the software.

(a) In connection with the study of the very first two *TESS*-discovered compact hierarchical triple stars (TICs 167692429 and 220397947 – see below, under point 2.a), we implemented into the software package the calculation of the net spectral energy distribution (SED) of any multiple stellar systems (this moment up to six stars) and its fit to the observed passband magnitudes (in more than a dozen passbands). Simultaneously, pre-calculated PARSEC isochrone tables (Bressan et al., 2012) in a three-dimensional grid of [stellar mass, metallicity and age] triplets were also added to the package which is used to constrain the stellar radii and temperatures through a trilinear interpolation method. Therefore, now, we are able to determine accurately such fundamental stellar parameters as the masses, radii, temperatures even in the absence of spectroscopic measurements. In addition, the joint fitting of all photometric, ETV, SED, (and, if available, radial velocity – RV) data with the simultaneous use of the PARSEC isochrones allows us to determine further interesting astrophysical parameters. These include the age and metallicity of the investigated system, the interstellar extinction toward the triple or multiple star. It also provides the distance, which can be obtained either independent of the astrometric (Gaia) distance, or this latter (or, more precisely, the Gaia parallax) can be used e.g. as a Gaussian prior to constrain more accurately the other global parameters (Borkovits et al. 2020a).

(b) In connection with the discovery of the first two sextuple stellar systems which consist of three eclipsing binaries (EBs), we made LIGHTCURVEFACTORY to be able to handle to model (2+2)+2 type hierarchical sextuple stars, too. Furthermore, we developed also a new small accessory code which makes it possible to disentangle in successive steps the lightcurve of the blend of three EBs (independent on their physical connection), producing not only the phase-folded curves of each EBs, but their cleared, individual timeseries, too. This allows us to determine mid-minima times for ETV analysis of all three EBs in a system (Powell et al., 2021).

(c) We improved the analytical ETV curve solver OMINCFIT (Borkovits et al., 2015) incorporating the ability to fit an additional, fourth-body light-travel time (LTTE) solution too, together with the third-body LTTE + dynamical perturbations + apsidal motion fits. This new feature was used for the first time for the preliminary, analytical analysis of the ETV curve of TIC 220397947, which was found to be a (2+1)+1 hierarchical quadruple system (see below, under point 2.a – Borkovits et al., 2020a).

(d) We published the Transit and Light Curve Modeller (TLCM) code (Csizmadia 2020). This code is able to perform a joint radial velocity + transit/occultation light curve + beaming, ellipsoidal, reflection effects fit + a noise modlei fit. It works well for those exoplanetary systems where the proximity effects of binary stars are small or negligible. The noise model is based on wavelets. The approach was widely tested and the results are quite satisfactory: even at low signal-to-noise ratios the system and noise parameters can be retrieved with high accuracy (Csizmadia et al. 2021).

2) Discovery and/or complex analysis of individual multiple stellar systems (having stellar components from 2 to 6)

(a) We identified and analysed in a comprehensive manner the compact hierarchical triple stars TICs 167692429 and 220397947. The two EBs are located in and near to the Southern Continuous Viewing Zone (SCVZ) of *TESS* spacecraft. Therefore, they were almost continuously observed during Year 1 of the mission (and of course, during the current Year 3, too). We discovered their ternary nature through the large amplitude, non-linear ETVs. For the comprehensive analysis, we included ground-based SuperWASP data, too. In the absence of RV measurements, we used SED data and PARSEC isochrones to constrain the temperatures and other parameters of the stars. We were able to determine the stellar parameters with an accuracy of 1-2% and orbital ones with accuracies of 0.1% or better. While the more compact TIC 220397947 (P_in=3.55d; P_out=77.1d) was found to be an almost coplanar system (i_mutual=0.6deg), in the case of TIC 167692429 (P_in=10.26d; P_out=331.5d) the mutual inclination of the two orbits is ~27 deg, which leads to the precession of the orbital planes with a period of about 70 years. Therefore, we predict that the eclipses of the inner pair will disappear around 2028. We have also showed that in some periods in the past the system did produce extra or, outer eclipses, and we were able to detect such an extra eclipse in the archive SWASP data. In the case of TIC 220397947 we found some long-term timing discrepancies between the former SuperWASP and the recent *TESS* ETV data. We explained this discrepancy with the presence of a less massive fourth stellar component revolving on a ~2700-d-period outmost orbit. Therefore, we concluded that TIC 220397947 is probably one of the most compact quadruple stellar systems of (2+1)+1 hierarchies (Borkovits et al., 2020a).

(b) We discovered and analyzed the first two triply eclipsing triple star systems discovered by *TESS*. TIC 209409435 was observed only during ~50 days in the first year of *TESS* mission. Therefore, we organized an international, multi-site observing campaign to obtain further, follow-up photometric data. Then, with the combination of *TESS* and archive SWASP observations and the new campaign lightcurves, ETV curves determined from these data, and available passband magnitudes for SED analysis, we obtained again very accurate astrophysical and dynamical parameters for the three stars. We found that the slightly eccentric 5.7d-period inner binary consists of two solar-like nearly twin stars, while the slightly more massive third component revolves on a moderately eccentric (e_out=0.40), P_out=121.9d period orbit. The triple system is extremely flat (i_mutual=0.24 deg) again, which makes the triple dynamically stable and provides strict constrains on the formation channels of such a system (Borkovits et al., 2020b). We carried out a similar analysis for TIC 278825952. Former SuperWASP observations were available, so we used these data during our analysis, too. This latter triple is less compact, the inner and outer periods are P_in=4.78d and P_out=235.6d, respectively. Like the previous triple, the inner pair is formed by two near twin stars (slightly more massive than our Sun), too. In addition, the inner and outer orbital planes were also found to be aligned within 0.5 deg. The dynamically interesting feature of this system is that the wide outer orbit was found to be almost circular (e_out~0.003), which is quite unusual for such an orbital separation (Mitnyan et al., 2020a). Note that the analysis of TIC 278825952 has been formed a significant part of the PhD theses of CoI Tibor Mitnyan (defended in 2021).

(c) We investigated some compact, doubly eclipsing quadruple stellar systems with our package LIGHTCURVEFACTORY, too. These are (in the order of the appearances of the corresponding scientific papers) TIC 278956474 (Rowden et al., 2020), BG Ind (Borkovits et al., 2021) and TIC 454140642 (Kostov et al., 2021). All the three systems have been found to be quite compact with outer periods in the range of 430 and 900 days. Each systems are very remarkable from different aspects. The four stars of TIC 278956474 were found to be very young in age of some 10 million years. The brighter pair of BG Ind was a known, bright eclipsing binary. We have shown that it is orbited by an eclipsing pair of two red dwarfs in a ~730-day-period orbit. We confirmed also that the most massive component of the bright binary is just now evolving from the main sequence on its way to the giant branch. Finally, TIC 454140642 is a dynamically very active, compact quadruple, exhibiting huge, quick orbital perturbations on timescales of months to 1-2 years.

(d) We also discovered and analysed the very first sextuple stellar system which contains three pairs of EBs in a hierarchy of (2+2)+2. The object TIC 168789840 is located in constellation Eridanus and formed by two short (1.6 and 1.3 days) period eclipsing binaries orbiting each other on a probably 3.7-yr-period medium orbit. This quadruple subsystem forms a wide, but gravitationally bound further "binary" system with the 8.3 days period third EB. The fundamental parameters of the six stars, and the orbital parameters of the three inner orbits were also determined (Powell et al., 2021).

(e) We took part in the new analysis of VW LMi, the shortest known outer period (P_out=355d – but see point 2g, below) quadruple system of 2+2 hierarchy. We detected spectroscopically the apsidal motion of the 7.93-day-period, non-eclipsing inner binary. From the absence of any signs of orbital plane precession we concluded that the planes of the outer orbit and of the longer period inner, non-eclipsing pair should be fairly coplanar, i. e. the mutual inclination should be less than 10 deg (Pribulla et al., 2020).

(f) We investigated the magnetic activity of the K-dwarf component in the pre-cataclysmic binary system V471 Tauri. We used space photometry, high resolution spectroscopy and X-ray observations from different space instruments to explore the main characteristics of magnetic activity. We found that 5-10 per cent of the apparent surface of the red dwarf was covered by cool starspots. We found evidences on weak differential rotation. Our results suggest that frequent flaring could have a significant role in heating the corona. We concluded that the magnetic activity of the red dwarf component in V471 Tau was strongly influenced by the close white dwarf companion. The periodic appearance of the inter-binary Hα emission from the vicinity of the inner Lagrangian point was in correlation with the activity cycle (Kővári et al., 2021).

(g) Besides the closed studies having published results, we are carrying out ongoing investigations on further interesting multiple stellar systems, as follows:

- Five triply eclipsing triples discovered in Year 2 of *TESS* on the northern hemisphere. For all of them we organized intercontinental multi-site photometric (and, for the brighter ones, spectroscopic) follow up campaigns. (We expect at least two additional Q1 publications from these studies this year.)
- Two additional doubly eclipsing quadruple stars, including the one having the shortest known outer period 2+2 type quadruple system. Both quadruples exhibit quick, large amplitude dynamical perturbations. They are also involved in our continuous, ongoing, international spectroscopic and photometric follow up campaign.
- The second known sextuple star system formed by three eclipsing pairs. We have all the necessary data to publish the discovery and analysis paper, therefore, the only remaining task here is to write the paper.

3) Investigation of period variations of large samples of eclipsing binary stars

For the reasons, described in the introduction, these studies have not been finished yet. The current, ongoing investigations are as follows:

(a) Large area of the original *Kepler*-field was re-observed in Sectors 14, 15, and a smaller section also in Sector 26. With the use of these new data (and gathering some other, ground-based points extracted from SWASP and/or our own follow up photometric observations) we reanalyzed the ETV curves of the majority of the 222 CHTs identified in our previous survey (Borkovits et al., 2016 – the paper on which the present research project is based on). We refined the orbital and dynamical parameters in several systems. Moreover, due to the longer data length we were able to identify dozens of further, longer period CHT candidates in the original *Kepler*-field. We haven't published the results yet, because we decided to wait for the this summer new observations of *TESS*, as between 24 June and 20 August 2021 the spacecraft will re-observe this region with a much better time resolution than on the summer of 2019. As far as these new data will be available this autumn, we will include them into the analysis and publish the results.

(b) Besides the confirmed and candidate CHT-s in the original Kepler field we carried out also similar ETV studies of *Kepler*-discovered eccentric EBs to detect apsidal motions (both classical and relativistic ones) on the time-scale of more than a decade. With the combination of the derived apsidal motion periods and other ETV and lightcurve parameters we calculated the internal structure constants of two dozens of such EBs. The study will be the part of a PhD thesis of János Sztakovics (ELTE) supervised by the PI, and the corresponding paper is under preparation.

(c) The ETV survey of the Northern Continuous Viewing Zone (NCVZ) of TESS.
From an international collaboration, we received the most complete (yet unplublished) list of variable stars showing eclipse-like variations observed in at least one *TESS* Sector. For the ETV survey, we sorted out 5139 objects from this list that are in or near the NCVZ and have at least eight sectors of *TESS* observations available. This amount of data should be sufficient to detect the signals of light travel time effect and/or dynamical perturbations caused by additional components

in the ETVs of these of objects in order to increase the known sample of compact hierarchical triple or multiple (candidate) systems. For this purpose, we obtained the light curves of the above-mentioned 5139 sample objects from the *TESS* Full-Frame Images with a convolution-based differential photometric pipeline based on the FITSH software package (Pál 2012). We plan to analyze these systems using a newly developed interactive program with a graphical user interface (GUI) utilizing the Tkinter module of Python. This program allows the user to quickly load and view any raw light curve with several useful interactive features that help to analyze the light curve and quickly derive the ETV curve of an object. The already implemented features are: i) interactive detrending of the raw light curve using the WOTAN package (Hippke et al. 2019); ii) multiple period searching methods e.g. Lomb-Scargle Periodogram, Box Least Squares (BLS) Periodogram and Phase Dispersion Minimization (PDM) in order to determine the orbital period of the system; iii) reference epoch determination with the calculation of the (folded) orbital phase curve; iv) determination of the times of eclipsing minima or out-of-eclipse maxima with the fitting of higher-order polynomials; v) displaying the ETV curve of the object calculated from the previously determined minima/maxima using the previously found orbital period and reference epoch. We tested the above-mentioned features for around 50 different objects and it works as intended allowing the quick determination of the ETV curves and fast analyses of each system by eye. We have one more key feature to be implemented before starting the complete analysis of all objects: a coherent way to save the latest results in a database that will allow us to do more complex external analyses on the candidate systems and also to load the previous results from the database if it is available for a specific light curve opened in the future for any re-analysis that will ensure reproducibility. We will present this work and its preliminary results during the 2nd *TESS* Science Conference in a poster. We expect to finish the analysis of all light curves which will allow us to find all the candidate hierarchical systems in and near the NCVZ during this summer and we plan to publish the results of the survey in a Q1 journal. Moreover, after some minor modifications, our GUI could be used for any sets of light curves, hence we also plan to make it publicly available as a general, interactive light and ETV curve analyzer.

4) Other, miscellaneous results connected to *TESS* targets

(a) We analysed the light curve of the M5.5 dwarf Proxima Centauri obtained by *TESS* in Sectors 11 and 12. In the ~50 day long light curve we identified and analyzed 72 flare events. The flare rate was 1.49 events per day; in total, 7.2% of the observing time was classified as flaring. The estimated flare energies were on the order of 10^30-10^32 erg in the TESS passband (~4.8times higher in bolometric energies, but on the same order of magnitude). Most of the eruptions appeared in groups. Two events showed quasi-periodic oscillations during their decay phase with a timescale of a few hours. The oscillations could be caused by quasi-periodic motions of the emitting plasma or oscillatory reconnection. From the cumulative flare frequency distribution we estimate that superflares with energy output of 10^33 erg are expected to occur three times per year, while a magnitude larger events (with 10^34 erg) can occur every second year in average. This reduces the chances of habitability of Proxima Cen b, although earlier numerical models did not rule out the existence of liquid water on the planetary surface. We did not find any obvious signs of planetary transit in the light curve (Vida et al., 2019, ApJ, 884, 160).

b) As part of our ground-based program to support *TESS*-data analysis, we collected optical echelle spectra on 12 bright contact binaries at 17 nights. We derived new radial velocity curves from our observations. For quantifying the apparent chromospheric activity levels of the systems, we subtracted self-constructed synthetic spectra from the observed ones and measured the equivalent widths of the residual H_alpha-profiles at each observed epoch. Our well-sampled dataset allowed us to study the short-term variations of chromospheric activity levels as well as to search for correlations between them and some basic physical parameters of the systems. Fitting the radial velocity curves, we re-determined the mass ratios and systemic velocities of all observed objects.

We found that chromospheric activity levels of the studied systems show various changes during the orbital revolution: we see either flat, or one-peaked, or two-peaked distributions of equivalent width vs. the orbital phase. In the first case the activity level is probably constant, while the latter two cases suggest the presence of one or two active longitudes at the stellar surfaces. Our correlation diagrams show that mean chromospheric activity levels may be in connection with orbital periods, B–V color indices, inverse Rossby numbers, effective temperatures of the primary components and temperature differences of the components. At the same time, no clear trend is visible with respect to mass ratios, inclinations and fill-out factors of the systems. A- and W-type contact binaries in our sample show similar distributions at each of the studied correlation diagrams (Mitnyan et al. 2020b).

c) We developed a single, basic model to fit the long-term RV and ETV (or, in the context of exoplanets: transit timing variations – TTV) caused by tidal interactions, and applied the model to the WASP-18Ab system. We estimated the Love number of the planet from the observed periastron-precession. The best model fit to the archival radial velocity and timing data of WASP-18Ab was obtained with a Love number of the massive (10 MJup) hot Jupiter WASP-18Ab: k2,Love = 0.62(-0.19+0.55). This causes apsidal motion in the system, at a rate of 0.0087 +- 0.0033°/days ~ 31.3 +-11.8 arcsec day^-1. When checking possible causes of periastron precession, other than the relativistic term or the non-spherical shape of the components, we found a companion star to the WASP-18 system, named WASP-18B which is a probable M6.5V dwarf with 0.1 M_sun at 3519 AU distance from the transit host star. We also find that small orbital eccentricities may be real, rather than an apparent effect caused by the non-spherical stellar shape (Csizmadia et al., 2019).

d) We detected a new brown dwarf around a fast rotating Am-type star in the *TESS* light curve products. This is the first brown dwarf known around an Am-type star, named TOI-503b. We performed radial velocity follow-up measurements and determined the mass, radius and orbital elements. We could not decide whether this brown dwarf formed in situ or it moved to its present-day 3.6 days orbit via tidal migration. (Šubjak et al., 2020)

Departures from the original research and financial plans

Besides the reversal of the priority of some proposed research points (reasoned in the introduction of this closing report) there were a few additional departures from our original research and financial plans, as follows:

– We proposed to carry out a general ETV study of the EBs in the SCVZ of the *TESS* spacecraft. In the meantime, however, due to an informal agreement with the research group lead by Jerry Orosz (Dept. Astron., San Diego State Univ.) we changed to the NCVZ, leaving the southern zone to the American colleagues.

– As was mentioned above, the unexpectedly large number of serendipitious discoveries of extra eclipsing systems amongst those TESS target that have been observed only in a few sectors made it necessary to organize international follow up observing campaigns on one side, and carry out frequent follow up observations also with the instruments available for us. For this latter task we paid some, originally not planned, part-time research employment for Mr. István Csányi, a young PhD student at Baja Observatory. Moreover, for the organization and management of the international campaigns we employed also in a part-time non-researcher employment Ms. Krisztina Braun, librarian of Baja Observatory.

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