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Complex Analysis of Today's and Future Space Photometry of Multiple Stellar and Planetary Systems

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We aimed to develop new models and methods (both analytical and numerical) to answer the challenge of the large amount of unprecedently accurate space-borne photometric data obtained almost continuously in long time-windows by small aperture space telescopes dedicated for photometry in the last decade, data that are pouring in during present days too, and will continue in the near future as well. Originally we planned to develop one global software package handling in the same time both eclipsing stellar multiple and transiting exoplanetary systems. Later, however, for the partly divergent tasks related to the stellar and planetary analyses, and the almost disjunct groups of eclipsing binary and exoplanet researchers, we decided to divide the project into two independent sections. In what follows, first we list our results on multiple stellar systems and then, in the second part, on exoplanets.

1. Results on multiple stellar systems

a) <u>Development of a new software package for the complex spectro-photodynamical analysis of various, multi-site observations of binary, triple and multiple stellar systems</u>

Based on the PI's former triple star lightcurve emulator code (Borkovits et al. 2013) we developed a new, complex software package for the modeling and analysis of never-before-seen special features of various extraordinary binary and multiple systems discovered by recent space telescopes. The most characteristic improvements of the code, compared to the most frequently used standard lightcurve solvers (e. g. WD code – Wilson, 2008, and further references therein; and PHOEBE – Prša & Zwitter, 2005) are as follows.

(1) The following configurations are supported: (i) regular (eclipsing) binary system; (ii) hierarchical triple system (with or without inner and/or outer eclipses); (iii) a blend of two independent (eclipsing) binaries; (iv) 2+2 hierarchy quadruple system (mutual and multiple eclipses between all bodies are enabled); (2+1+1) hierarchy quadruple system (mutual and multiple eclipses are also enabled).

(2) Simultaneous treatment is possible for (max.) 5 light curves (in predefined, various filters), 1 radial velocity (RV) curve for each body, and 1 or 2 eclipse timing variation (ETV) curves of the innermost binaries.

(3) Rectangular coordinates and velocities of each component can be calculated either (i) analytically, from Kepler equations; or (ii) numerically, i. e., with numerical integration of the orbital equations of the motion and the Eulerian equations of stellar rotation, respectively (photodynamical treatment).

(3) Doppler-boosting is built in.

(4) Stellar pulsations and any other quasi-period lightcurve distortions can be inherently filtered out with Fourier-polynomials.

The parameter optimization is carried out with a Markov-Chain Monte Carlo (MCMC)-based parameter search, using our own implementation of the generic Metropolis-Hastings algorithm (see e. g. Ford 2005).

We developed another, auxiliary code suite designed for helping the analysis – and, in particular, identification – of oscillation modes on components of eclipsing binaries. While preparing to include the code into the main software package (in the near future), we implemented a method which determines the originating stellar component for each oscillation mode, as in general any, or all, components of a multiple system may be susceptible for oscillations. The method employs the general modulating effect of the eclipses on the oscillations, and fits generic amplitude (and, optionally, phase) modulation curves on the eclipsing parts of the light curve for the respective oscillation mode.

With the use of the different versions of this software package we analyzed more than a dozen eclipsing binary and multiple systems (most of them discovered by Kepler and CoRoT satellites). Here we highlight only the most interesting results.

We analysed the recently discovered rare sdO+dM eclipsing binary (EB) Konkoly J064029.1+385652.2 that shows extreme deep eclipses and reflection effect. Our model showed that the hot sdO primary irradiates its red dwarf companion, heating its substellar point to about 22500 K. The photometrically determined, unusually large, but robust log *g* value suggests that the sdO primary is a pre-WD (white dwarf) star, i. e. it is on an evolved position on its way to become a white dwarf (Derekas et al. 2015).

The 18 days period eccentric EB KIC 7177553 was identified as a possible host of a 1.45-yr-period non-transiting circumbinary planet via our ETV analysis (Borkovits et al. 2016 – see below). In order to confirm our findings we have arranged for ground based followup RV observations. These measurements led to an unexpected result, as we found that KIC 7177553 is an SB4 quadruple system containing besides the already known 18 days period EB another 16.5 days period, non-eclipsing spectroscopic binary. We carried out a combined spectroscopic and photometric analysis for the quadruple and determined the main orbital and astrophysical parameters (Lehmann et al., 2016).

We also analysed the quadruple systems with EPIC numbers of 212651213, 220204960, and 21917635. The K2 lightcurves of these targets exhibit the blend of two EBs. By the use of our new developments, we were able to carry out the lightcurve analyses without requiring any a priori disentanglement of the signals of each binary. We have collected further RV, high resolution adaptive optics (AO) and ETV data from multisite followup observations and determined accurate astrophysical and orbital parameters for these systems. EPIC 212651213 was found to be a quintuple star system. EPIC 220204960 was found to be a gravitationally strongly interacting, very close quadruple, while for EPIC 21917635 we showed that one of the two EBs is a rare red straggler-type semi-detached system (Rappaport et al. 2016, 2017; Borkovits et al. 2018).

We analysed the phase-folded lightcurves of five CoRoT EBs for which the ETV curves suggested the presence of additional, dynamically interacting stellar components. We combined the results of the lightcurve analyses to the ETV analyses (see below) to obtain more reliable stellar masses and confirm or reject the tight third-body hypotheses (Hajdu et al., 2017).

We carried out a spectro-photodynamical analysis of the triply eclipsing triple system EPIC 249432662. We analysed simultaneously the ~80 days long K2 lightcurve, ground-based followup photometric and RV observations, and the ETV curves calculated both from space and ground-based photometry. Our analysis revealed that this 188 days outer period triple has an extremely flat configuration (the mutual inclination of the two orbits is i_m=0.2-0.4 degrees). The inner, regurarly eclipsing pair consists of two mid-M type red dwarfs with similar masses. The outer, brightest component was found to be a mid-K dwarf with a mass close to the sum of the inner pair. The flatness and the mass ratios of this triple system render it to be a very important case study for the binary and multiple star-formation theories (Borkovits et al., 2019a).

The most complex system that we have investigated with the most recent version of the spectro-photodynamical software package was HIP 41431 (EPIC 212096658). We carried out a joint analysis of three campaigns of K2 lightcurves, ETV curves, 20 years long SB3 RV observations and additional photometric followup eclipse observations carried out at Baja Observatory, Hungary. We concluded that this 2+1+1 hierarchy-type system is to date the tightest quadruple system of its kind. We found that the inner triple contains three very similar stars with 0.62-0.64 solar masses, while the fourth component weighs 0.35 solar masses. The mutual inclinations are small, but definitely differ from zero. Therefore, the orbital planes precess. We detected and succesfully modeled this precession through the eclipse depth variations of the innermost EB. Quick, dynamically triggered apsidal motion is also nicely visible, both in the case of the innermost and the middle orbits, and our model gives back well the observations. We found spectroscopically that despite the old age of the system, the stellar spins are non-synchronized, and illustrated with long-term numerical integrations that the rotation of the innermost stars is likely chaotic due to the combination of dynamical and tidal effects (Borkovits et al., 2019b).

b) Analytical studies and their applications on the search for new multiple star systems

We improved the former, second order theory of the long period (P_{out} time scale) perturbations in the frame of the hierarchical three body problem. We included all the third-order perturbation terms, furthermore, the most significant short-period (P_{in} time scale) terms were also involved (up to second order). Furthermore, the „apse-node" time-scale perturbation terms were also added. In this way we were able to break down some degeneracies between the parameters which existed in the previous, second order theory of Borkovits et al. (2011). By the use of the obtained perturbation equations we gave directly the analytical form of the ETVs of any EBs having an additional third, distant companion. For solving the inverse problem, we developed a software package to fit the analytical formulae to the observed ETVs of such EBs. We describe the complete analytical model, the software package, and the first applications as well, in Borkovits et al. (2015).

In Borkovits et al. (2016) we extended our investigations for all EBs and ellipsoidal variables which were observed by Kepler space telescope in its 4-year-long primary mission. We determined third-body solutions by ETV method for 222 EBs. Amongst them, for 62 systems we were able to find a combined light-travel time effect (LTTE) plus dynamical perturbations solution, while for the remaining 160 EBs we gave pure LTTE solution. For a large portion of the 62 dynamical systems we were able to determine complete 3D configurations of these systems (including the determination of key dynamical parameters like the mutual inclination), and individual stellar masses as well. We carried out a significant statistical analysis on these triples. Thanks to our study the population of triples with known mutual inclination experienced a six-fold increase. Thus, this paper serves also as an important base observational reference for triple star evolutionary studies, too (see, e. g. Moe & Kratter, 2018).
A good indicator of the importance of the Borkovits et al. (2016) paper is the fact that the Web of Science database counts 32 independent citations within the first 24 months from its publication, ranking it into the highest 5% papers of its field.
The results of these two works formed a substantial part of the DSc theses of the PI (Borkovits, 2016), which was succesfully defended in 2018.

We applied the same method for EBs observed by the CoRoT space telescope. Despite the significantly shorter data lengths, we were able to identify five short-period, dynamically interacting triple star candidates. Furthermore, we have discovered the first two triply eclipsing systems in the CoRoT sample (Hajdu et al., 2017).

Most recently we studied the short period EBs observed in the frame of the galactic bulge part of the OGLE IV survey. We have identified 992 potential hierarchical triple (or multiple) system candidates exhibiting LTTE, and investigated their statistical properties (Hajdu et al., 2019).

2. Results on exoplanet systems

Code development. The *Transit and Light Curve Modeller* code (TLCM) was published in Csizmadia et al. (2015) and its updates were submitted to MNRAS in 2018 (Csizmadia 2019). The 2015 version capabilities were:

- fit of the Mandel & Agol (2002) spherical body-model to photometric data including quadratic limb darkening effects and linear or parabolic baseline-variations;
- taking the effects of contamination and eccentric orbits into account;
- fit of the occultation light curves;
- optimization via the Harmony Search realization of Genetic Algorithms. The results were refined by a Simulated Annealing chain; error estimation was based on the analysis of the χ^2 values.

The 2018 version has the following additional options:
- fit of the RV-curves jointly with the the light curves of SB1 and SB2 systems as well;
- including photometric and radial velocity jitter;
- fitting $\sqrt{e}\sin\omega$ and $\sqrt{e}\cos\omega$ instead of e and ω to avoid possible biases at low eccentricity orbits;
- fit of the RV offsets between different instruments that often have different zero-points;
- a simplified version of the Rossiter-McLaughlin-effects is included;
- linear and quadratic RV-trends are considered and fittable (c.f. Smith et al 2019, below);
- Keplerian RV-curve of a second planet can be fitted (no perturbations are considered);
- beaming, ellipsoidal and reflection effects were added. The spectral indices are calculated by concolving a spectral library with the response function of several space telescopes. The ellipsoidal effect is based on Kopal (1959). The reflection effect uses for optional phase-curves: a simple cosine-function of the phase, a Lambertian-sphere, the Kane-Gelino (Kane & Gelino, 2011) phase-function appropriate for gas giants, or the phase-function given by Kopal (1959). These ones rectify the light curve;
- red noise analysis via wavelets (Carter and Winn 2009) to assess the effect of correlated noise;
- MCMC and bootstrap analyses are added to get more accurate error bars and uncertainties;
- user defined functions to describe LC baseline variations (e.g. the roll angle variation of the planed CHEOPS telescope was used in simulated CHEOPS data to better describe its flat-field variations);
- usage of Gaia DR2 parallax data and/or spectroscopic log g data as further constraints on the fit and on the derived absolute parameters.

An extract of the most important results.

The code was applied in Eigmüller et al. (2106), where the discovery of a very rare F+dM eclisping binary system was announced. The companion has only a mass of 0.188±0.014 M_sun and a radius of 0.234±0.009 R_sun. The primary is not synchronized yet, indicating that the system is young (~250 Myr).

During the course of checking exoplanet candidates detected by the CoRoT space satellite mission, we have identified 1846 new variable stars in the CoRoT SRc02 field, only 30 of which were known previously. 241 of them are eclipsing variables and we presented light curve solution for nine more interesting ones (Klagyivik et al. 2016). Another new variable star was discovered in Csizmadia et al. (2016). The search for new exoplanet candidates with the Berlin Exoplanet Search Telescope (BEST) yielded 26 previously known, 314 suspected variable and 1829 newly discovered variable stars in Puppis. We have analysed many of them (Dreyer et al., 2018).

The TLCM was used to analyse the following, newly discovered transiting exoplanets and brown dwarfs:
– K2-98b (a Neptune-sized planet, orbiting an F-star on a 10-days orbit; Barragán et al. 2016).
– K2-99b (a P=18.3 days period, eccentric hot-Jupiter; Smith et al., 2017). Our new RV analysis, carried out by TLCM has revealed the presence of a 460 days period, 10 jupiter mass second planet, too (Smith et al. 2019, to be submitted, including Csizmadia as co-author).
– K2-60b, a rare class of exoplanets at the very edge of the “sub-Jovian desert”; and K2-107c, an inflated hot Jupiter (Eigmüller et al., 2017).
– K2-180b, a mini-Neptune at 9 days orbital period, and K2-140b, a 7 days orbital period hot Jupiter (Korth et al. 2019).
– K2-111b, an inflated hot Jupiter around a G3V star, of which we detected the non-transiting mate, K2-111c by radial velocity variations (Fridlund et al. 2017).
– K2-141b, an ultrashort period planet (USP, P_{orb} = 6.7 hours) around a K7V type star. It has only five earth-masses (Barragán et al. 2018a).
– K2-137b, another similar USP with P_{orb} =4.3 hours around an M-dwarf (Smith et al. 2018).
– K2-139b, a temperate Jupiter on a relatively long, 29 days orbit around a K0V type star (Barragán et al. 2018b).
– EPIC 220501947 b and K2-237b, two inflated hot Jupiters (Smith et al. 2018).
– EPIC 2193881932b was found to be an 5.3 days orbital period transiting brown dwarf, located in the brown dwarf desert and in the Ruprecht 147 open cluster (Nowak et al., 2017).

We investigated the statistical properties of the so-called brown dwarf desert, i. e. the paucity of brown dwarfs as companions to FGK-dwarf stars at a<5 AU. We found that the number of the transiting brown dwarfs is less than 20, and showed that the brown dwarf frequency is increasing from 0.2% at 0.1 AU to 0.6% at 5 AU (Csizmadia et al., 2015; Csizmadia, 2016; Csizmadia and Smith, 2019).

We studied the occurrence rates of circumbinary planets. We gave upper limits for the number of Jupiter, Saturn-, and Neptune-sized planets in co-planar orbits for different orbital period ranges (Klagyivik et al. 2017).

We re-analysed all the available RV data of WASP-18Ab. From the tidal part of the periastron precession rate we determined the Love-number of this exoplanet ($k_{2,Love} = 0.62^{+0.55}_{-0.19}$). This is the first direct measurement of the periastron precession and the Love-number of any exoplanet utilizing the RV and timing data (Csizmadia, Hellard & Smith, 2019).

We analyzed the K2 light curve of the TRAPPIST-1 system. The data suggest a rotation period of P_{rot} = 3.295 days. The light curve shows several flares, the strongest of which is comparable to the strongest eruption ever observed on the Sun (the Carrington event). Approximately 12% of the flares were complex, multi-peaked eruptions. The flaring and the possible rotational modulation shows no obvious correlation. The flaring activity of TRAPPIST-1 probably continuously alters the atmospheres of the orbiting exoplanets, which makes them less favorable for hosting life. After its appearance in arXiv there was more than 100 news reports of the paper (Vida et al., 2017).

3. Departures from the original research and financial plans

– In order to support the scientific carriers of young researches, (with the permission of the Council of Physical Sciences) we involved three PhD students in the project works during the course of the ongoing research (J. Sztakovics, T. Hajdu and T. Mitnyan). They helped to fulfil the proposed research plan with significant contributions, and furthermore, firstauthored three refereed research papers (Hajdu et al., 2017, 2019; Mitnyan et al., 2018).
– As mentioned previously, we separated the two codes developed for multiple stellar systems, and exoplanets. This decision gave us higher flexibility during the code development phase. Furthermore, the independent development of the two software offered excellent possibilites to cross-check the parallel features of the two softwares agains each other.
– During the summer season of 2018 the uninterruptible power supply (USP) unit of the host institute (Baja Astronomical Observatory) suffered a fatal damage. Therefore, in the last more than half year the continuous, undistorted electric power service, which was essential for the long-term computational runs, could not be guaranteed. The unexpected power outages caused delays of weeks in the computational analyses. In this situtation, although not featuring in the original financial plan, purchasing a new UPS unit from the available residual budget was essential for the succesful conclusion of the project.

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