Complex, Spectro-Photodynamical Analyses of Triply Eclipsing Triple Star Systems Discovered with TESS

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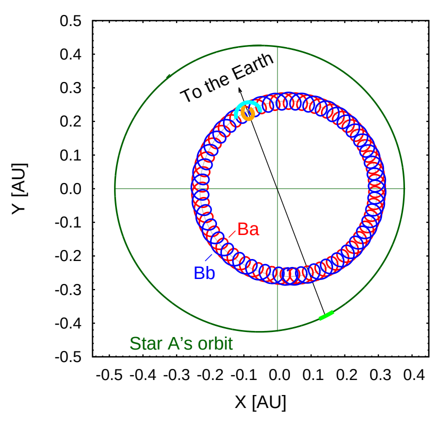
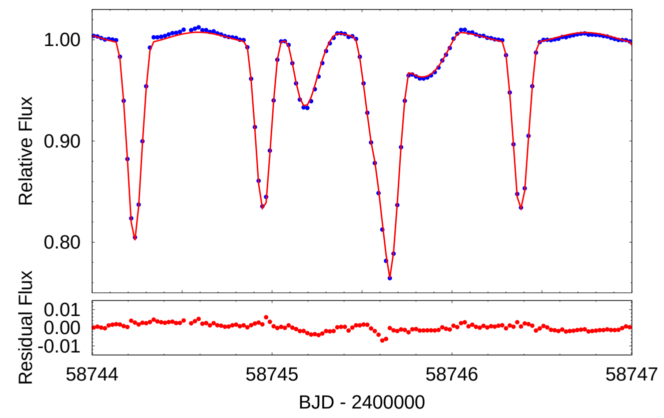
With TESS we have discovered about a dozen new triply eclipsing triple stars, i.e., hierarchical triple or multiple stellar systems where the outer stellar component recurrently eclipses the inner eclipsing binary or is eclipsed by it. The outer orbital periods of these systems were found to be between 1.5 months and 1 year, and therefore, in most cases, the orbits of the EBs depart significantly from simple Keplerian motion which is manifested by strong eclipse timing variations (ETVs). For a few case studies we present the full process of studying such systems beginning with their identification through an initial characterization of the 'third body' eclipses, to follow-up ground-based observations and the use of archival data, and then to the final complex photodynamical modelling. The latter includes joint (multi-epoch, multi-band) lightcurve, ETV curve, radial velocity curve (if available), and composite SED analyses. Such studies can allow for the complete characterization of the system parameters, including the detailed orbital architecture. A surprising number of overall flat systems have been found.





Discovery and follow up of triply eclipsers

- Serendipitious discoveries of 'extra eclipsers' are relatively easy tasks. It needs "only" the careful investigations of thousands of (eclipsing binary) light curves in each sectors. This was done mostly with eye by a hawk-eyed group of enthusiastic citizen astronomers who call themselves the Visual Survey Group (VSG).
- Most of the identified extra eclipsers were, however, observed only during a few TESS sectors. For example, TIC 209409435 was observed only in sectors 3 and 4 in Year 1 (and produced pairs of extra eclipses in both sector). Similarly, TIC 193993801 was observed in three sectors during Year 3 (and luckily, produced, three sets of extra eclipses, one in each sectors). But, the most typical is that only one extra eclipse has been observed, as in TIC 388459317. Therefore, we know almost nothing even about the period of the distant, third companion.
- First steps of analysis: (1) checking eclipse timing variations (ETVs); these can help to characterize the period and mass ratio of the outer system; (2) preliminary light curve analysis of the inner eclipsing binary to find out what kind of stars we observe; (3) past and future monitoring of the target, i. e., looking for historical and survey observations (e.g. SWASP [1], ASAS-SN [2], etc.) and then, organizing international photometric follow up observing campaign(s) and, if the target is bright enough, acquiring radial velocity measurements.
- Photometric follow up observations – small 0.3–1m aperture telescopes operated by mostly (but not exclusively) backyard astronomers. In the first stage of the follow up the aim is to observe regular eclipses of the inner binary for determining ETVs which may lead to constraints on the outer period, and predictions of the most probable time window of the forthcoming outer eclipse. In such a manner we have observed several extra eclipses, most of them due to the continuously refined predictions derived from the previous regular eclipse observations (e.g. TICs 209409435, 052041148, 193993801), but we have obtained serendipitious extra eclipse observations (TIC 388459317) as well.

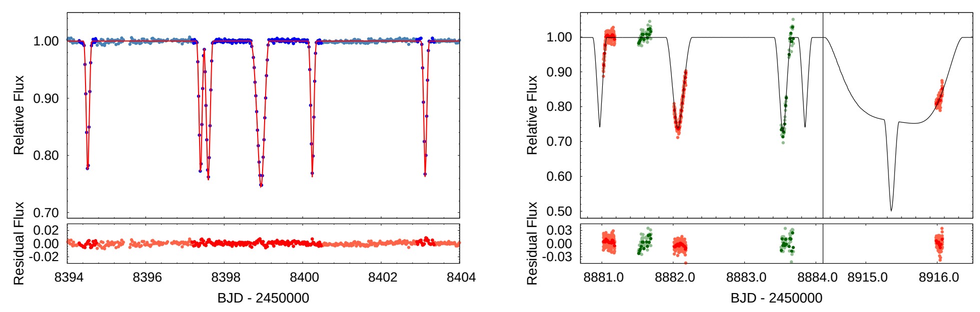


Fig. 1. *Left: 9-day section of TESS FFI light curve of TIC 209409435 with the first set of observed extra eclipses. Right: Two consecutive extra eclipses observed (partly) during our photometric follow up campaign. (Black line represent the best photodynamical model.)*

Spectro-photodynamical analysis

- Lightcurvecatory sofware package has been continuously developed since 2011 (the modelling efforts of one of the very first triply eclipsing system, HD 181068, discovered by Kepler space telescope – [3,4,5]).
- From a dynamical point of view: the software is able to handle binary, hierarchical triple, quadruple (both hierarchicies of 3+1 and 2+2) and sextuple (of [2+2]+2) systems. The orbital motions and the rotations of the stars optionally can be numerically integrated. Tidal effects are also considered [6].
- From an observational point of view multiple passband photometric light curves (including any kinds of extra eclipses) can be modelled simultaneously with ETV and RV curves
- Since the 2020 version [7] grids of PARSEC isochrones [8] have been also built in, which can be used for a stellar evolutionary model constrained fitting of fundamental stellar parameters. Moreover, it has also been used for net spectral energy distribution (SED) fitting. (However, we plan to include another, evolutionary model-independent SED fitting procedure in the near future, too.)
- For solving the inverse problem, and exploring the complex parameter space of the targets under investigation a Markov Chain Monte-Carlo based parameter search has been applied.

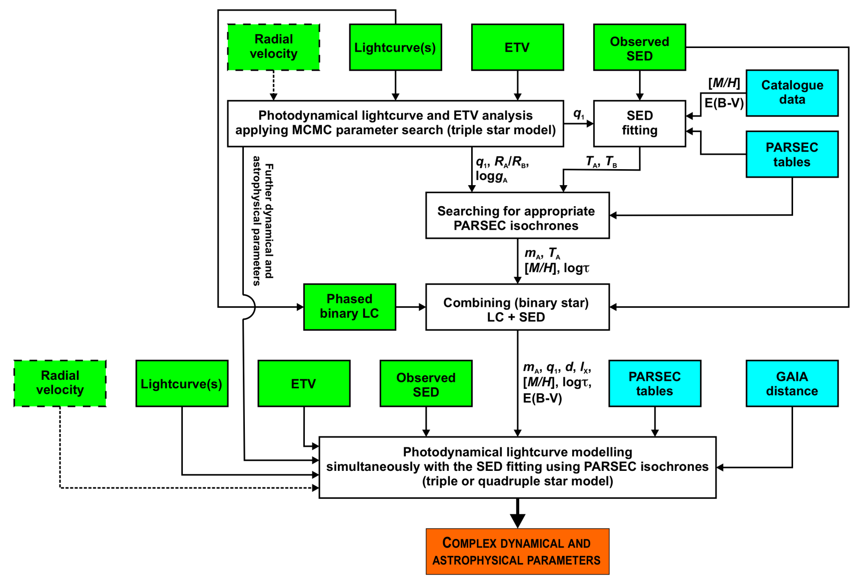


Fig. 2. *Flow diagram of the different steps and levels of the complex spectro-photodynamical analysis realized with the sofware package Lightcurvefactory.*

Results on individual triply eclipsing systems disvovered with TESS

Here we presents results obtained with complex (spectro-)photodynamical analyses on the three best studied TESS triply eclipsers.

- *TIC 209409435* is comprised of three very similar solar type stars. The two components of the $P_{\rm in} = 5.72$d period, almost circular ($e_{\rm in} = 0.004$) inner binary are perfect twins ($m_{\rm A} = m_{\rm B} = 0.90 \pm 0.03\,\mathcal{M}_\odot$), having a mass ratio of $q_{\rm in} = 1.002 \pm 0.003$. The slightly more massive third star ($m_{\rm C} = 0.98 \pm 0.04\,\mathcal{M}_\odot$) revolves on $P_{\rm out} = 121.9$ d-period, moderately eccentric ($e_{\rm out} = 0.3965 \pm 0.0001$) orbit. The triple system is exceptionally flat ($i_{\rm relative} = 0.24 \pm 0.08$ deg), which makes this tight, $\sim 5^{+1}_{-2}$ Gyr-old system stable over the nuclear lifetime of the stars [9].
- *TIC 278825952* is the only triply eclipser in our sample that is located in the Southern Continuous Viewing Zone and, therefore, there was no need to organize a follow-up observing campaign. The $P_{\rm in} = 4.781$ d-period inner binary consists of slightly evolved, near twin stars of masses $m_{\rm A} = 1.12 \pm 0.08\,\mathcal{M}_\odot$ and $m_{\rm B} = 1.09 \pm 0.07\,\mathcal{M}_\odot$, while the less massive ($m_{\rm C} = 0.75 \pm 0.03\,\mathcal{M}_\odot$ tertiary component has an outer period of $P_{\rm out} = 235.5$ d. Both the inner and the outer orbits were found to be practically circular, and, similar to the previous triple, this system was also found to be flat ($i_{\rm rel} = 0.5 \pm 0.3$ deg) [10].
- *TIC 193993801* is one of the shortest outer period ($P_{\rm out} = 49.4$ d) triply eclipsing system, discovered with *TESS*. Photometric and spectroscopic follow up observations have revealed that the timings of the regular and the newer extra eclipses cannot be described well with numerical integration of the three-body motion. Therefore, we assume that the system also contains a fourth, less massive, more distant companion revolving on a $P_{\rm outmost} = 1\,300-1\,600$-day-period orbit. While the innermost ($P_{\rm in} = 1.43$ d) and middle orbits were found to be almost circular and aligned ($i_{\rm rel} \sim 0.8$ deg), the outmost orbit seems to be quite eccentric ($e_{\rm outmost} \sim 0.53$) and inclined within $10-20$ deg. Another interesting fact that the $m_{\rm Aa} = 1.32 \pm 0.02\,\mathcal{M}_\odot$ primary of the innermost pair is seemingly a bit more evolved than the slightly more massive tertiary ($m_{\rm B} = 1.36 \pm 0.04\,\mathcal{M}_\odot$), which might arise from either a slightly different age of the components (within a few 100 Myrs) or some former interaction between the components of the close pair. (Note, the other two masses are $m_{\rm Ab} = 1.19 \pm 0.02\,\mathcal{M}_\odot$ and $m_{\rm C} = 0.21 \pm 0.07\,\mathcal{M}_\odot$.)

Summary

- We identified dozens of eclipsing binaries exhibiting extra fadings due to a more distant third stellar component in TESS FFI lightcurves.
- We organized (and are continuously organizing) international photometric (and, optionally, spectroscopic) observing campaigns for better characterization of these interesting systems.
- Combining space and ground based photometric data, eclipse timing variations information, radial velocity data (if available) and multiple stellar energy distribution data and, optionally, stellar evolution information, we carried out complex spectro-photodynamical analyses of some triply eclipsing triple systems from the *TESS* sample and obtained fundamental astrophyisical, and dynamical parameters with great accurracies.
- Observations and analyses of further triply eclipsing systems are in progress.

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