Multiply eclipsing candidates from the TESS satellite

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ABSTRACT

We present a catalogue of the Transiting Exoplanet Survey Satellite (TESS) targets that show multiple eclipses. In all of these stars, we detected two sets of eclipses, for which their two distinctive periods can be derived. These multiple stellar systems could either be doubly eclipsing quadruples or triple-star coplanar systems showing eclipses on the outer orbit in addition to the inner eclipses. In total, 116 systems were found to be doubly eclipsing, while 25 stars were identified as triply eclipsing triples. Several confirmed blends of two close sources were not included in our analysis. All these systems were identified by scanning the known eclipsing systems taken from the Variable Star Index database and checking their TESS light curves. The average period of the dominant pair, pair A, is 2.7 days in our sample, while for the second pair, pair B, the average period is 5.3 days. Several systems show evident eclipse timing variation (ETV) changes even from the short interval of the TESS data, indicating possible period changes and short mutual orbit. We also present evidence that the system V0871 Cen is probably a septuple-star system of architecture (Aa-Ab)-B-C-D. Most of the presented systems are adequately bright and show deep enough eclipses for observing, and therefore we call for new ground-based observations for these extremely interesting multiples. Owing to this motivation, we have included also the ephemerides for both pairs of each system, our catalogue also contains their depths of eclipses and the light-curve shapes as extracted from the TESS data. These new ground-based observations would be very useful for further derivation of the mutual movement of both pairs on their orbit via detection of the ETVs of both pairs for example.

Key words. binaries: eclipsing – binaries: close – stars: fundamental parameters

1. Introduction

More than 200 yr ago, it was proposed that the brightness changes in Algol are caused by an obscuring body and its orbit around the main star (Goodricke 1783). This was the moment when eclipsing binary research was born. However, two centuries passed before it became clear that eclipsing binaries could provide absolutely unique insight into basic stellar properties, such as masses, radii, and luminosities. Their role in current astrophysical research is undisputable (see e.g. Southworth 2012), and nowadays, in the era of huge photometric surveys and projects, their number is increasing rapidly, meaning that they can be used to calibrate existing stellar models of evolution.

In addition, thanks to large surveys, significantly reduced scatter, and a tremendously increasing number of known systems, we are also able to discover and study much more complicated objects. For example, the huge survey Optical Gravitational Lensing Experiment (OGLE; Udalski et al. 1992) was used to identify about a thousand new candidate triple stars by studying period changes using the so-called eclipse timing variation (ETV) method; see Hajdu et al. (2019).

Moreover, a relatively new group of objects, nowadays known as doubly eclipsing systems, are also mostly being discovered thanks to large photometric surveys like OGLE, Kepler, Corot, and TESS (see e.g. Soszyński et al. 2016; Lehmann et al. 2012; Hajdu et al. 2017; and Kostov et al. 2021). These objects show two distinct eclipsing periods coming from one point source on the sky. The study of such stars should bring us fresh insight into stellar formation mechanisms (see e.g. Tokovinin 2021). Nevertheless, if both these eclipsing binaries are really bound to each other and share a common orbit around their barycenter, both should also share the same distance, age, and metallicity. This is an important aspect, which should be tested when analysing a particular system, and can be used to set tight constraints on our model.

Our main motivation for discovering and studying such systems is the fact that they represent ideal astrophysical laboratories. They allow us to study celestial mechanics in ‘real time’, the dynamical influence between the inner and outer orbits, Kozai cycles, the dynamical evolution of the orbits, such as precession and inclination changes, and so on. Moreover, with enough such 2+2 quadruples with known orbits, one can study their origin, and subsequent evolution. We aim to decipher whether they are products of disc fragmentation, or N-body dynamics, and to investigate the mean motion resonances of both inner pairs. Many questions remain to be answered, and larger and more robust samples will bring useful information.

2. The selection process

The first doubly eclipsing system confirmed showing two eclipsing periods was V0994 Her (Lee et al. 2008). Nowadays the group comprises about 160 doubly eclipsing systems with both periods being known. However, some of them could still be blends of two close-by components not connected gravitationally, and the mutual orbit is only known for a few of these latter. This is a serious problem, especially in dense star fields: one cannot definitively prove that the signal of two periods comes to our telescope from one point source on the sky. The large survey OGLE discovered several dozen doubly eclipsing systems

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in dense Large and Small Magellanic Clouds (LMC and SMC) fields, and in closer Galactic bulge fields (Graczyk et al. 2011; Pawlak et al. 2013; Soszyński et al. 2016).

In addition, quite recently it was discovered that quite a significant fraction of new doubly eclipsing binaries are found in already known and bright eclipsing binaries. The problem is usually that these additional eclipses were missed because of their small amplitude (compared with the dominant pair, as in V0482 Per; Torres et al. 2017), or because these stars are sometimes easily too bright for modern telescopes (as in BU CMi; Jayaraman et al. 2021). Possibly the most remarkable example is the system BG Ind, which was studied in detail with ground-based photometry (Rozyczka et al. 2011) having not previously noticed anything suspicious. However, TESS data revealed that BG Ind is the nearest doubly eclipsing system (Borkovits et al. 2021), and it was being missed simply due to the overly shallow photometric amplitude of pair B. Sometimes only small parts of the light curves near eclipses are observed, and the rest is monitored only very rarely, which leads to non-detection of the additional eclipses (like for V0498 Cyg; see Southworth 2022).

Taking into account all these aspects and limitations, we decided to use the extremely precise and freely available database of the TESS satellite (Ricker et al. 2015), and to scan as many potential systems as possible. Nowadays, probably the most complete database of information on variable stars is that one running under The American Association of Variable Star Observers (AAVSO), named The International Variable Star Index (VSX; Watson et al. 2006), comprising about a million stars in total; we downloaded their data, plotted their light curves, and checked for additional eclipses. Plotting TESS fluxes versus time, but for others with periods longer than 0.5 days. In addition, we plotted and checked with 

For some of the systems, the additional eclipses were seen directly when plotting TESS fluxes versus time, but for others we needed first to subtract the dominant eclipsing binary shape and later to search for additional eclipses on the residuals. Plotting the TESS photometric data in the phased light curve with a particular period is a straightforward task with the available pro-

Our goal was not analyse these systems in detail, but only to present a catalogue of candidate systems; that is, stars for which one simple period was not able to describe all the eclipses identified in the TESS data. In total, 141 such stars were found, among them 116 doubly eclipsing ones and 25 candidates of triply eclipsing triple stars. Several other systems were also found, as suspected, but their nature is still rather questionable (most often the contact W UMa-type shape and short periodic pulsation patterns are too similar).

Our method of disentangling the complete photometry into two separate light curves of both pairs is rather straightforward. We used the program named Slic龃 (version 2.991), which uses a phenomenological model for the phased light curve. Such a preliminary light curve fit can be subtracted and one can easily see whether some additional eclipses are also visible on the residual light curve. Where this was the case, we used a period-searching algorithm to detect the secondary period $P_2$ (using a PDM method).

As one can see from our Fig. 1, our detected candidate doubly eclipsing systems nicely fill the incomplete statistics. Up to now, most of the detected doubly eclipsing systems were found in the OGLE fields, in both the LMC and SMC, and the Galactic disc and bulge. However, these OGLE data comprise somewhat biased photometric data (e.g. observing strategy over the years, data cadency of observations, etc.), and therefore also the detected doubly eclipsing systems are definitely slightly different from those in the TESS data (almost complete detection of binaries with $P < 27$ days). There are two particularly important aspects here. At first, the cadence of the OGLE data is typically only one observation per night, but the overall time-span (on the LMC and SMC) is more than 10 yr. On the other hand, the TESS data provide continuous undisturbed photometry over 27 days. The second important aspect is the typical scatter, or error, of individual data points. OGLE provides data with about 0.01 mag scatter, while the scatter for TESS data is an order of magnitude lower. Therefore, the level of eclipse depth detectable in both surveys should also be rather different and many of the systems detected by our method here are definitely not visible in the OGLE data. Finally, the angular resolution of the TESS and the OGLE data is also very different.

On the other hand, what Fig. 1 also shows us is the fact that our sample of newly detected systems (marked in blue) show a much higher tendency to be closer to the Galactic disc than the rest of the other bright TESS targets. Qualitatively, the stars

\[ \text{https://www.vizier.cern/ch/starlist/...5} \]
closer than $10^\circ$ from the disc comprise about three-quarters of our sample, but contain only about one-quarter of the TESS stars. It is therefore questionable as to whether the number of doubly eclipsing binaries is higher in the Galactic disc (due to higher star density, and perhaps therefore higher probability of blending). However, we prefer an alternative explanation, namely the fact that all the stars in our sample come from the known eclipsing systems, which are mostly being discovered in large photometric surveys detecting most of their variables preferably closer to the Galactic disc.

Concerning the two periods, the more prominent one is typically that of pair A (which usually has deeper eclipses), but some exceptions exist. Our primary period of pair A is always that given in the VSX catalogue, and the period of pair B is the new derived one.

One might ask how we deal with the blending problem within the large TESS pixels. In the huge majority of the systems, we were also able to identify both sets of eclipses from older ground-based photometry with better angular resolution. These were namely the ASASsn (Kochanek et al. 2017; Shappee et al. 2014), ZTF (Masci et al. 2019), and SWASP (Pollacco et al. 2006) data. The ZTF survey in particular was a very useful source of photometry, with its high angular resolution helping us to rule out the blending of the two close-by sources. Several blends of two close stars were also proven as a by-product of our analysis (like V0432 CMa, ASASSN-V J020003.56+452605.2, and ASASSN-V J123052.13-475634.5).

4. Results

In total, we detected 116 systems as 2+2 quadruple doubly eclipsing candidates. The huge majority of these should be characterised as EA + EA (see Table A.1, and Fig. 2). This phenomenological classification only tells us that our method is able to discover such systems more easily, simply because the two periodic curves are more easily disentangled into the two periods and their shape is definitely ‘eclipse-like’. All of the disentangled light curves of both pairs are plotted in Figs. A.1–A.8. For all of the systems, we use its original name within the VSX database and give also the TIC number for identification and coordinates in Table A.1.

Figure 3 shows for illustration how difficult it can be to detect the additional eclipses of pair B from the ground when only poorly sampled data are available. A good example is the eccentric system V0384 Cen, which has been observed many times in the past, with nobody noticing the distorted shape of the minima and that these deviations are periodic, coming from the unseen additional pair. This is a typical example of a bright system observed in the past, where a second pair has an order of magnitude smaller photometric amplitude. Unfortunately, the observers usually only observe the eclipses, and sometimes even their bottom parts only. In such cases, the detection of pair B is often quite difficult. This highlights the great advantage of the continuous TESS data, where targets are observed with superb precision for many days in a row.

The systems classified as triply eclipsing triples (see e.g. quite recent study by Borkovits et al. 2022) were easily distinguished from the doubly eclipsing quadruples because of the shapes of the additional eclipses (‘double peak’) and also their uniqueness (i.e. long orbits, long periods, only rarely observed in the TESS data). These systems are given below in Table 1. The other ground-based photometric surveys were usually also used for detecting the outer periods of the third body. This was partly successful for several systems (because of their large depths and the long-lasting monitoring in these surveys) and we also give their outer periods in the last column of Table 1. Their light curves, which in addition to the ‘ordinary’ eclipses also show other eclipses are given in Fig. A.9.

Probably the most interesting system seems to be ASASSN-V J101237.44-594344.8, which shows large variations of ETV for the inner pair A and also exhibits eclipse-depth variations (both in the TESS data as well as in the older ground-based photometry). In the following list, we briefly mention those systems that were found to be interesting in some aspect resulting from our analysis. Some of them were found to be located very close to the mean motion resonance configuration, as already proposed in our previous paper (Zasche et al. 2019), and studied also theoretically by Tremaine (2020).

- ASASSN-V J004727.28+624315.4 : very eccentric pair B (secondary eclipse in phase 0.26).
- ASASSN-V J020306.68+624315.4 : very eccentric pair B (secondary eclipse in phase 0.26).
- ASASSN-V J024221.82+625403.6 : almost exact 2:1 resonance (only 0.2% off).
- V1018 Cas : eccentric pair A, close to 4:3 resonance.
- V0417 Aur : change of classification here. Former classification as pulsating-eclipsing EA is now more probably an EA + EW system.
- ASASSN-V J064048.28-224659.0 : eclipses of pair B are visible in TESS data only in 2020, and are missing in 2019 and 2018 (orbital precession?).
| RA [J2000.0] | Dec [J2000.0] | VSX Target name | TESS number | Mag_{peak} | P_D1 | Mag_D1 | P_D2 | Mag_D2 | HJD−2450000 | Comment |
|-------------|-------------|----------------|-------------|------------|------|--------|------|--------|-------------|---------|
| 04 31 15.65 | +57 43 45.12 | ASASSN-V J043115.65-374510.1 | TIC 356324779 | 13.229 | 8833.09262 | 3.476856 | 0.28 | 0.28 | 8837.5 | 86.693 d outer period, eccentric |
| 06 26 37.57 | –03 23 50.64 | ASASSN-V J062637.57-032350.6 (1) | TIC 4266588 | 13.714 | 9210.1994 | 1.832875 | 0.15 | 0.15 | 9219.67 | 123.48 d outer period, eccentric |
| 07 02 36.30 | +15 46 40 | WISE J070236.0-155456 | TIC 5791867 | 15.351 | 9219.77869 | 0.359096 | 0.29 | 0.29 | 9221.30 |
| 07 34 10.87 | +43 59 28.31 | ASASSN-V J073410.87+435928.3 | TIC 21079989 | 14.211 | 9520.75387 | 3.707533 | 0.12 | 0.12 | 9534.2 | 202.09 d outer period |
| 09 43 52.56 | –06 39 48.89 | ASASSN-V J094352.56-063948.9 | TIC 38328524 | 13.900 | 9275.60856 | 9.230 | 0.3 | 0.3 | 9546.15 |
| 10 12 37.44 | –59 43 44 | ASASSN-J101237.44-594344.8 | TIC 46310247 | 12.719 | 9290.50969 | 5.666999 | 0.11v | 0.09v | 8572.32 | 132.51 d outer period, eccentric |
| 10 39 09.91 | +41 35 49.59 | ASASSN-J103909.91+413549.6 | TIC 40549865 | 13.393 | 7958.469 | 1.426808 | 0.25 | 0.25 | 9289.42 |
| 11 00 23 | +40 43 41.6 | OGLE CAR_SCI_9699 | TIC 46704298 | 14.256 | 9123.45321 | 3.292551 | 0.24 | 0.24 | 9138.78 |
| 11 43 30.07 | –59 48 11.95 | ASASSN-J114330.07-594811.9 | TIC 26741300 | 12.880 | 8607.3378 | 2.57830 | 0.13 | 0.05 | 9349.45 |
| 12 57 59.68 | –53 55 45.54 | ASASSN-J125759.86-535545.5 | TIC 34680572 | 11.421 | 9340.3397 | 5.598930 | 0.17 | 0.17 | 8607.51 |
| 13 05 42.72 | –63 28 53.59 | WX Cru | TIC 73934478 | 13.780 | 9434.08589 | 0.837748 | 0.23 | 0.12 | 8604.05 | 60.27 d outer period, very deep |
| 12 26 36.55 | –12 53 57.48 | ASASSN-J122636.55-125357.5 | TIC 34612478 | 12.805 | 8591.06632 | 9.872767 | 0.33 | 0.33 | 8573.08 |
| 13 58 35.66 | +31 56 79.78 | KELT-100612 | TIC 73666043 | 11.669 | 8907.6404 | 0.8547985 | 0.01 | 0.005 | 8908.09 |
| 14 51 59.98 | –63 03 58.78 | ASASSN-J145159.98-630358.8 | TIC 29480397 | 12.957 | 9302.87869 | 0.837748 | 0.23 | 0.12 | 8604.05 | 60.27 d outer period, very deep |
| 17 04 25.49 | +46 35 33.58 | CSS-J170425.46+353353 | TIC 19385120 | 14.513 | 8986.3757 | 2.876069 | 0.19 | 0.19 | 9013.0 | 37.38 d outer period |
| 17 13 43.81 | +31 04 66.89 | W0735 Sco | TIC 47313245 | 10.349 | 9377.36748 | 1.20179 | 0.07 | 0.07 | 9368.49 | 285 d period, eccentric |
| 20 51 12.50 | –75 55 30.22 | ASASSN-NC0144.19-755530.2 | TIC 34783382 | 11.714 | 9300.99839 | 5.8662 | 0.39 | 0.20 | 8526.00 | 148.9 d outer period |
| 24 54 46.67 | +48 46 50.66 | WISE J183446.4+485066 | TIC 27985001 | 11.856 | 8595.38023 | 0.9295082 | 0.14 | 0.07 | 9402.11 | 165.28 d outer period? |
| 20 19 50.99 | +51 47 31.53 | KIC 0534674 | TIC 27323317 | 13.28 | 8700.09662 | 2.39047 | 0.6 | 0.57 | 9426.75 | known coplanar triple, see (Masuda et al. 2015) |

Notes: (t) Out-of-eclipse magnitude, (∗∗) independently discovered during preparation of the current manuscript, and recently published in Rappaport et al. (2022).
common barycenter. Due to the fact that the mutual movement of the A-B pair is only very slow, namely of the order of thousands of years (Zasche et al. 2009), and hence the probability of the mutual eclipse on such an orbit right now in the TESS epoch is very improbable, we have to conclude that the architecture of the whole system is as follows. The most inner two pairs are the 2.8 d and 2.09 d binaries (we name these Aa-Ab), accompanied by a more distant component B with its only poorly constrained orbit by Zasche et al. (2009). The much more distant C and D components are probably bound (due to their similar proper motion), but only very weakly. The whole system is likely septuplet. Its 2.8 d photometric variation was not noticed earlier because of is its much lower amplitude compared to the dominant pair A.

Finally, we also found the star ASASSN-V J124203.23-644513.2 to be extremely interesting. In addition to the two eclipsing periods of pairs A and B (periods 2.0725, and 1.4123 days), this system shows an eclipse observed by TESS (see Fig. 5). However, its shape is ‘double-peaked’, as in triply eclipsing triples, and its depth is similar to that of pair A, indicating that pair A is being eclipsed at that time. Three probable explanations emerge: (1) a quadruple 2+2+2+1 eclipsing system, which is also perfectly coplanar, meaning that even this mutual orbit is eclipsing; (2) a double eclipsing system with one additional component (architecture 2+2+1+1) causing this eclipse; or (3) a blend of two unrelated stars, that is, two systems: a triple and a binary.

5. Conclusions

We carried out an analysis of all EA-type binaries from the VSX database (with $<15$ mag) in an attempt to identify additional eclipses in the TESS data. Our compilation of 141 systems is so far the most extensive among other similar studies. The database we present should be useful to observers and keen astronomers for detailed follow-up monitoring of these interesting targets. For this reason, we give the ephemerides for both eclipsing pairs, but also their eclipse depths. These are crucial parameters for prospective future observations.

Such monitoring is potentially very important because of the chance of detecting the ETV for both pairs, which could be used to prove their quadruple nature. According to our previous findings (Zasche et al. 2019), we believe that most of these candidate stars will be confirmed as quadruples thanks to intensive ground-based observations in the upcoming years. Such long-lasting monitoring will be our main task for the future seasons. We have already begun to collect data with our group of keen astronomers using their relatively modest equipment, which is nevertheless quite adequate for such a task. We find a combination of two pieces of software, namely SIPS (for reduction of the CCD frames) and SILICUPS (for plotting and subtracting the individual light curve shapes), to be particularly suitable for reducing and analysing such complicated systems.

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Note added in proof. Following submission of the present manuscript, an independent paper dealing with the same topic was published by Kostov et al. (2022). The authors present a group of 97 doubly eclipsing systems found in the TESS database, but identified with a different method (scanning all stars instead of only known eclipsing binaries, as we did). Due to this difference in approach, there is relatively little overlap in the systems we find; in total 18 systems, which are marked with an asterisk in Table A.1.

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| RA [J2000.0] | DE [J2000.0] | VIXX Target name | TESS number | EB type | Mag |
|----------------|----------------|-----------------|-------------|--------|-----|
| 8964.1830 | 49.5465 | A&A 664, A96 (2022) | 10496.30 | 54.45 | 13.78 |

**Table A.1. Doubly eclipsing candidates.**

Notes: - Out-of-cycle magnitude, $V_{oc}$, from UCAC4 catalogue (Zacharias et al., 2013), or Guide Star Catalog II (Lasker et al., 2008).
- Independently discovered during preparation of the current manuscript, and recently published in Kostov et al. (2022). The columns $D_H$ and $D_E$ denote the approximate depths of primary and secondary eclipses of both pairs based on the TESS data.

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Fig. A.1. Light curves of both pairs as disentangled from the original TESS photometry. Plotted in ascending order of Right Ascension.
Fig. A.2. Light curves of both pairs as disentangled from the original TESS photometry, continuation.
Fig. A.3. Light curves of both pairs as disentangled from the original TESS photometry, continuation.
Fig. A.4. Light curves of both pairs as disentangled from the original TESS photometry, continuation.
Fig. A.5. Light curves of both pairs as disentangled from the original TESS photometry, continuation.
Fig. A.6. Light curves of both pairs as disentangled from the original TESS photometry, continuation.
Fig. A.7. Light curves of both pairs as disentangled from the original TESS photometry, continuation.
Fig. A.8. Light curves of both pairs as disentangled from the original TESS photometry, continuation.
Fig. A.9. Light curves of triply eclipsing triples. The eclipses of the inner pair are denoted by short abscissae in blue for primary, and red for secondary eclipses. Extra eclipses are clearly visible.