TIC 452991707 & TIC 452991693 AS A CANDIDATE SEXTUPLE SYSTEM WITH THREE ECLIPSING BINARIES

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ABSTRACT

We present the discovery of a rare system detected in the TESS data showing three different eclipsing-like signals. TIC 452991707 & TIC 452991693 seem to be the second such system on the sky, whose two components separated about 16$''$ are gravitationally bounded, or comprise a co-moving pair. The three periods detected from the TESS data are: $P_A = 1.46155$ d, $P_B = 1.77418$ d, and $P_C = 1.03989$ d, respectively. The A and B periods belong to TIC 452991707, while the C comes from the component TIC 452991693. The pair A shows the deepest eclipses, and its orbit is very slightly eccentric. The third period C has lowest amplitude (eclipsing or ellipsoidal nature), but originates from TIC 452991693, which is connected to A+B because both visual components share similar proper motion and distance. Long-term collection of data from older photometry from various surveys also shows that the two inner pairs A and B orbit around their barycenter. Its period is probably of a few years, but for a final derivation of its orbital parameters one needs more up-to-date data. Hence, we call for new observations of this amazing system.

Subject headings: binaries: eclipsing – stars: fundamental parameters – stars: multiple.

1. INTRODUCTION

The classical eclipsing binaries are being used for decades for deriving the precise stellar parameters such as radii, masses or luminosities. Also can be used as distance indicators, even outside of our Galaxy (see e.g. Graczyk et al. 2014, or Paczynski 1997). We can also study the stellar evolution in them, calibrating different models, detect the tidal interaction in closer systems or discover the additional components in these systems (see e.g Guinan & Engle 2006, and Borkovits et al. 2016). However, some of the eclipsing binaries were found worth of studying simply because they show some unexpected behaviour and only closer look to them would be able to reveal what is actually going on in them.

Twenty years ago there was not known any multiple stellar system with two eclipsing binaries. Since the discovery of V994 Her (Lee et al. 2008) proving its doubly eclipsing nature detecting the two eclipsing periods there. Just two years ago it was not known any sextuple system with three eclipsing binaries inside. Since the discovery of TIC 168789840 (Powell et al. 2021), and its three eclipsing periods. And now, it seems that on the whole sky there are probably much more similar systems like this containing three eclipsing binaries. Should we expect also a discovery of an octuple system with four eclipsing binaries soon?

2. SYSTEM DISCOVERY

The system TIC 452991707 & TIC 452991693 was discovered during our scanning of the TESS photometry of interesting sources, trying to identify there some additional eclipses, remarkable systems, triples with coplanar orbits causing extra eclipses on the long orbit, etc. There exist a huge group of undiscovered and still unstudied systems showing two sets of eclipses in the TESS data waiting to be discovered and analysed. And this is one of them.

The TESS photometry was extracted using raw TESS data with the lightkurve tool (Lightkurve Collaboration et al. 2018). After then, in both sectors 17 and 18 also an additional subtraction of longer trends was done with a polynomial fitting.

The most problematic issue when reducing the photometric data seems to be the fact that the TESS satellite provides only poor angular resolution (pixel size is 21$''$) and the signal from two different close-by sources (about 16$''$) fall into the same pixel. Hence, its photometry is combined together and such blending is usually problematic when having no other ground-based follow up observation with higher angular resolution. The field of both close components is being plotted in Fig. 1.

Already from the TESS photometry there were detected two main periods and after their subtraction also the third one. We named the most pronounced eclipse as pair A (having about 1.46 day period), while the other one slightly shallower as pair B (period 1.77 days). The third periodicity C of about 1.04 days is harder to detect.
there, due to its lowest amplitude. Consider that the pair A has the amplitude of photometric variation over 0.1 mag, pair B over 0.05 mag, while pair C of about 0.035 mag. When plotting the residuals after subtraction of both A and B pairs, the periodicity of pair C is clearly visible. However, its nature would not be so clear at the first sight. One can for instance doubt whether it is an eclipsing, or a pulsational pattern with 0.52 day period. But when analysing the data in more detail taking into account the most plausible fit of A and B, then one can clearly see that both primary and secondary eclipses are clearly of different depths (see below Fig. 3). Hence to conclude, such a light curve shape shows that it cannot be caused by pulsations, but rather caused by ellipsoidal variations of a close binary.

3. THE TESS DATA

As one can see from the illustrative picture of the light curve obtained with the TESS satellite in Fig. 2, the combined light curve is rather complicated and the star cannot be easily detected from the ground-based data. The TESS data provide continuous coverage of many days in the raw, but suffers from its large pixels. We cannot easily separate the signal from the two sources, and have to analyse the whole light curve of all three signals together.

This task was done iteratively in several steps. In each step a preliminary fit of a particular pair was subtracted and the residuals were analysed for the other two pairs. After that, removing another pair, trying to find the best solution (when subtracting all three light curves, one should obtain almost stochastic behaviour of residuals around zero value).

We used the program PHOEBE (Prša & Zwitter 2005) for the light curve analysis, a freely public available software based on the Wilson-Devinney method (Wilson & Devinney 1971). Several simplifying assumptions have to be made due to missing spectroscopy and having only very limited information in our hands (these were mainly the assumption of synchronous rotation, and limb-darkening coefficients being interpolated from the tables of Van Hamme (van Hamme 1993) and using the logarithmic law). The most serious seems the be the issue of its effective temperature (of its primary component). Several different sources provide very different values of the $T_{\text{eff}}$, ranging from 5101 K (Gaia DR2 2018) to 7017 K (Bai et al. 2019), and one cannot easily judge which one to prefer. However, thanks to quite moderate angular separation of both sources TIC 452991707 & TIC 452991693 of about 16″, we are able to obtain different photometric information ranging over large wavelength values for both of them. These observations coming mostly from large-scale photometric surveys, or satellite databases, can be then used to estimate the temperatures using the spectral energy distribution (SED) fitting. We greatly acknowledge the use of freely available web services VOSA (Bayo et al. 2008), which was used for this purpose. As a result we roughly estimated that the star TIC 452991707 is slightly cooler than TIC 452991693. We fixed the primary temperature values for TIC 452991707 as 5300 K, while for TIC 452991693 as 5600 K for the whole light curve analysis, see below. On the other hand, as we have tested the effect of using different primary temperature values is only very small on the resulting Eclipse-Timing Variation (ETV) diagrams and the question of the whole architecture of the system.

The results of our fitting are given in Table 1. This table also provides the ephemerides for all three pairs for future observations. Both pairs A and B seem to be the detached binaries, pair A moreover with very slightly eccentric orbit ($e < 0.005$), but the pair C is probably a contact one. For the pair B the components should maybe better be interchanged because the secondary is larger, as well as more massive one. However, we prefer to leave the notation as it is due to the fact that now the primary minimum (the deeper one) is located at 0.0 phase. One can see a slight asymmetry of the light curves B and C, clearly evident near the quadratures. This can be caused by some photospheric spots, or maybe by some improper reduction as an artifact. We leave it as an open question, waiting for new better data to become available.
4. OTHER PHOTOMETRY

Besides the TESS data, there are also other sources of available photometry, obtained in ground-based observatories. The most extensive is the data set obtained during the ASAS-SN survey (Shappee et al. 2014, and Kochanek et al. 2017). This data provides excellent time coverage over four seasons, but at the cost of lower quality (small aperture of the telescope). However, all three pairs are visible.

Besides that, the star was also found in the database of the SWASP project (Pollacco et al. 2006), whose big advantage is a fact that it spreads our time span back to 2007. Besides that, also the ATLAS survey (Heinze et al. 2018) was used.

However, the most important at this place is to mention the photometric survey named ZTF (Masci et al. 2019). The reason why particularly this one is so important is the fact that it provides the best angular resolution of its photometry due to using larger telescope. Thanks to this fact, both close photometric sources were observed separately. And with these ZTF data we were able to identify that the variation of A+B comes from the southern target (i.e. TIC 452991707 = UCAC4 746-005302), while the C pair is located with the northern star (i.e. TIC 452991693 = TYC 3666-1030-1). Due to the fact that both A and B variations reside in the same photometric point on the sky, we still classify this target as a doubly eclipsing system.

5. SYSTEM ARCHITECTURE

Having known the sources of variability of all three periods, we should ask about the architecture of the whole system. Two main questions arise. Is there some evidence that these two close-by stars really constitute a bound multiple system? And secondly, can we provide some proof that also the A and B pairs are gravitationally bound together? Surprisingly, both answers are: Yes.

Both visual components are of similar type (same colours, same photometric indices – a kind of solar like stars). Both share about the same proper motion. And their parallax according to GAIA is also about the same: 0.3065 ± 0.0131 mas for TIC 452991707, while 0.2985 ± 0.0123 mas for TIC 452991693, according to GAIA DR3 (Gaia Collaboration et al. 2022). Hence, we can conclude that the stars compose a weakly bound system with very long orbital period, or at least a co-moving pair in our Galaxy. Having no information about the precise masses, we can only roughly calculate that the semimajor axis (projected separation leads to about 50kAU semimajor axis) and solar like stars imply the putative period of several Myr. In less dense stellar population (it is located in the outside part of our Galaxy) even so weakly bound system can survive for certain period of time.

Another question of A-B orbit was resolved using all available photometry and derivation of many times of eclipses of particular pairs in certain time epochs. A similar method was used previously for a similar system TIC
168789840 (Powell et al. 2021), or doubly eclipsing CzeV1731 (Zasche et al. 2020). Due to its rather shallow photometric amplitude the scatter of the pairs B and especially C are rather poor. But still we can definitely state that the pairs A and B orbit around each other with several-years periodicity (with the available data our analysis led to period of about 7 years). Orbital period of the pair C remains constant. For a final derivation of orbital parameters of A-B are the data too badly sampled in time and suffers from too large scatter. But their shape in antiphase is clearly visible with the available data now, see Fig. 4. Hence, its co-moving connection was proved, which could be a sextuple configuration. At this place it would be useful to emphasize how rare such sextuple systems are. According to our current knowledge, the most up-to-date version of the Multiple Star Catalog MSC (Tokovinin 2018) lists only 18 sextuple and 4 proved septuple systems on the whole sky nowadays.

We can also ask whether the two parallaxes from GAIA are reliable enough, and not biased due to the proximity of the stars. In former Hipparcos catalogue such an effect was being discussed several times that the close unresolved pairs yield spurious results on its parallax and proper motion. However, here the situation is much different due to the fact that both sources are about 16'' distant, well beyond any such effect could possibly play a significant role. Quite a different situation would be for the inner pair A-B, which orbits in much smaller separations. However, the two distances derived for each of the two stars TIC 452991707 & TIC 452991693 were derived from GAIA DR3, which should take into account also these binary and multiple stars orbits instead of single star solutions as in previous data releases.

6. DISCUSSION AND CONCLUSIONS

We present a very first analysis of a sextuple system candidate with three eclipsing periods and provide an evidence of the link between the components. Having only very limited information in our hands and with missing spectroscopy, we still deal with a bit preliminary picture of the system. However, the nature of the variability and its contribution to both close components is definite.
Our analysis led to finding that the mutual period of the A-B double is about $\approx 7$ yrs, and we can also derive the predicted angular separation of the A-B pair for a prospective interferometric detection. However, thanks to its quite small parallax, this semimajor axis resulted only in about 2 mas, which is unfortunately too low for such a faint star nowadays. The spectroscopy would be also useful for deriving the mutual orbit as well as the physical parameters of all components, however we would need quite a lot of observing time for such a target.

One can ask, whether in such a configuration (three very close orbits of several days, an intermediate orbit, and a long orbit of thousands of years) a system can be stable and exist for a longer period of time. Quite recently there was published a paper about V1311 Ori (Tokovinin 2022), where its outer-most orbit is of the order of a Myr long, and the author discussed whether it is still a bound system or a moving group/minicluster. The structure of our system resembles e.g. the well-known sextuple system Castor (= $\alpha$ Gem), where the respective periods also range in between a day and several thousands of years. Many other similar hierarchies can also be found in the Multiple Star Catalog (MSC), see Tokovinin (2018).

According to our knowledge there are about 300 doubly eclipsing systems known up to date. Only four of them are nowadays known to be sextuples with three eclipsing binaries. For two new candidates see a recent study by Kostov et al. (2022), while the very first sextuple system showing three eclipsing periods was TIC 168789840 (Powell et al. 2021). Hence, a brand new field of astrophysical research is now opening, thanks to the database of the TESS satellite.

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Fig. 4.— ETV diagram of the two inner pairs A and B with a preliminary fit of their orbit. Different colors denote different sources of photometry, while the filled and open circles represent the primary and secondary eclipses.
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