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Double eclipsing binaries

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Abstract. Double eclipsing binaries are still quite neglected type of objects. Despite the increasing number of candidates, a thorough study of these interesting systems is still missing. We started our campaign on these stars and even after one season several very interesting results appeared. At first, it seems that almost all of the candidate double eclipsing systems really constitute the rare quadruple stellar systems. Moreover, the final proof of quadruple nature can be done only on the photometric data (studying the period variations of both pairs). As a by-product also a mass estimation can be done using only the photometry, which is quite beneficial and unusual fact in stellar astrophysics. The lack of such systems on the northern hemisphere is also being discussed and a call for a systematic search is presented.

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

1. Introduction

Eclipsing binaries still represent the objects of crucial importance for our knowledge about the Universe, about the stellar structure and evolution, and others. Thanks to them we are able to calibrate our evolutionary models, we can derive the interior structure of the stars, derive their radii or study the stellar populations in and outside of our Galaxy (see e.g. Southworth 2012).

During the last decade there have also been discovered a special group of eclipsing binaries called double eclipsing binaries (or sometimes also doubly eclipsing binaries). These systems show two different sets of eclipses with different periods and durations of eclipses. Hence, we can speculate about their connection and consider them as gravitationally bound systems. The other possibility is that these are two independent eclipsing binaries at different distances projected into the same direction by a pure chance. In the dense fields also this possibility cannot easily be ruled out.

However, to prove their bound orbit is, in general, not easy. One way is to measure their radial velocities, and to detect the mutual movement around the common barycenter. For any such detection one needs high-quality spectra to successfully disentangle all the four components and consecutively to detect the mutual movement also the long-time baseline of observations. According to different studies (e.g. Duquennoy & Mayor 1991, or Raghavan et al. 2010), the outer periods of the third components in multiple-star systems are typically of the order of several years, decades, or centuries. Therefore, any such spectroscopic detection of the quadruple nature is very time consuming. Worth of mention is also the fact that many such systems are relatively faint, hence good spectroscopic observations are still quite tricky.

Another possible method proving that the two binaries are really bound to each other would be to detect there some dynamical perturbation of the two pairs. The easiest for photometric detection is maybe the detection of the changing orientation of the orbital plane of such systems, hence the changing eclipse depth of the binary (or both binaries). Such phenomena were discovered for several dozens of stars nowadays, see e.g. Juryšek et al. (2018), but as far as we know only for one double eclipsing system yet (Hong et al., 2018). The problem is that for detecting such perturbation the movement of the orbital precession should be rather fast (which is typically not the case), which means that the third body should have quite a short orbital period. The shorter the outer period, the more pronounced and faster the nodal precession (Borkovits et al., 2015).

2. Method

However, we introduced a different method. Our method seems to be much more effective and less demanding for high-quality data. We need no spectroscopy, and the use of photometry of large surveys (measuring, for example, the object only once per night) is sufficient. We used a classical and well-known method of period analysis of the eclipses (ETV method) using the hypothesis of a so-called light-time effect to the orbits of both pairs. When we incorporate both binaries into one joint analysis, we can get a complete set of orbital parameters of their mutual orbit. In fact the same method was first used for a well known (and first discovered) system V994 Her, see Zasche & Uhlař (2016).

As a source of photometric data we used mainly the OGLE catalogue (Udalski et al. 2008, and Udalski 2003), accompanied with our own measurements when available. The list of candidate double eclipsing systems was scanned and each system was considered to be potentially interesting. However, only those with adequately detached components having enough data points for subsequent analysis were included into our sample to be analysed.

The main result of our analysis is the first evidence that many of these double eclipsing binary candidates really orbit each other thanks to their ETV analysis. Two most promising examples of our analysis are plotted in Figure 1.

The light curves of both eclipsing binaries were analysed using the program PHOEBE (Prša & Zwitter, 2005). Thanks to this modelling of the light curves, we were able to derive the individual inclination angles of the inner pairs, relative radii of the components, their luminosity ratios, etc. Moreover, using these light

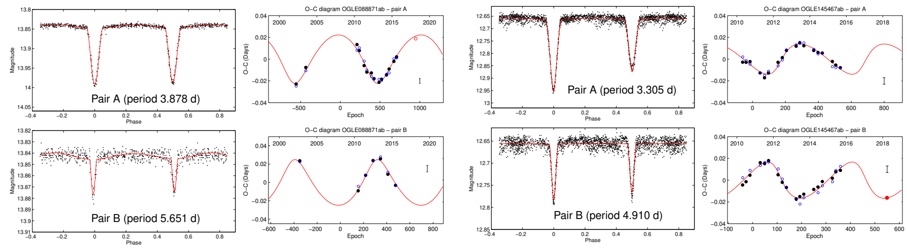

Figure 1. A sample of two systems found in the OGLE database with proved quadruple nature. Their light curves (left) as well as the ETV curves (right) are plotted.

curve templates also the times of the eclipses were derived using a method introduced earlier (Zasche et al., 2014).

From our analysis of ETV there resulted that the selected systems (see Figure 1) really comprise two eclipsing binaries which orbit around each other. Their mutual movement was detected via the ETV signals of both pairs. Hence, using this analysis also the mass ratios of both pairs can easily be computed from the amplitudes of the ETV variations of both pairs (because of knowing the inclination angles for eclipsing binaries $i \approx 90° \Rightarrow \sin i \approx 1 \Rightarrow M_A/M_B = A_B/A_A$). The mass ratio of both binaries is a crucial parameter for any further analysis. However, for a final derivation of the mutual inclination of the orbits one needs precise masses of both pairs, which can only be derived from spectroscopy. And the mutual orientation of the orbits plays a crucial role when discussing about the origin of the system as well as its future dynamical evolution.

Several systems showing their mutual motion have quite good coverage of their ETV diagrams, and can be definitely classified as quadruples. In total, we have detected 10 new proved quadruples. This is for the first time any such large portion of new quadruples using this new technique was detected. As one can see in Figure 1, the two different eclipses are rather deep and therefore the analysis was rather straightforward concerning the ETV analysis. What is still quite problematic was the analysis of their luminosity ratios (i.e. the third light values of both pairs). For other systems, with much worse data coverage or shallower minima, this task is still very questionable and the results inconvincing.

Nowadays we have several dozens of candidates for double eclipsing stars (88 in total), but which were not proved to orbit each other. Can we say something more general about these systems? What can be stated even with the present result is a fact, that certainly almost all of the double eclipsing systems constitute real bound quadruples. Why can we be so sure? We detected in our sample an occurrence rate of more than 40% of quadruples. However, our method is essentially sensitive only to those systems with the outer orbital period of several years. Below one year the result would be inconclusive due to poor data sampling of the ETV curves. And on the other hand, the orbital periods longer than 10 − 15 years would be also problematic due to the limited time span of our data. However, as it was published earlier (e.g. Duquennoy & Mayor 1991, or Raghavan et al. 2010), the typical periods of the distant components are an order of magnitude longer. Hence our method is quite insensitive to that detection and we only revealed a "tip of an iceberg". Moreover, also the mass ratio, as well as the orientation of the mutual orbit towards the observer, play a role. All of these limitation should be taken into account when trying to estimate the incompleteness fraction. Hence, we believe that practically all double eclipsing systems are parts of the quadruples.

One important aspect of the topic was not discussed. Due to the large photometric surveys OGLE we nowadays know a huge majority of such double eclipsing systems only on the southern sky. As one can see from Figure 2, most of the systems have low declinations and can only be observed from the southern observatories. We really demand more similar systems on the northern sky for prospective photometric observations using the world-wide net of variable star observers (having their instruments mostly on the northern hemisphere). Potentially, surveys like ASAS-SN (Shappee et al. 2014 and Kochanek et al. 2017) can serve as an ideal starting point for finding new candidates also on the northern sky.

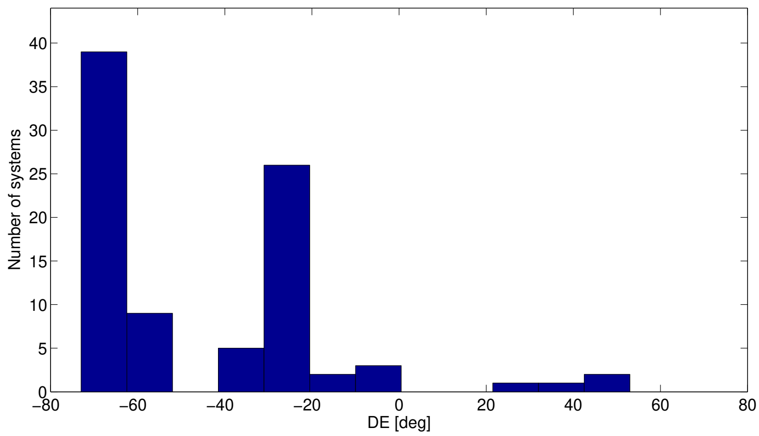

Figure 2. The histogram of declinations for the known candidate double eclipsing systems. The double-peaked shape is caused by the systems located in the Magellanic Clouds and the Galactic bulge from the OGLE survey.

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