TEN KEPLER ECLIPSING BINARIES CONTAINING THE THIRD COMPONENTS

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ABSTRACT

Analyzing the available photometry from the Kepler satellite and other databases, we performed detailed light curve modeling of 10 eclipsing binary systems that were found to exhibit a periodic modulation of their orbital periods. All of the selected systems are detached Algol type, with orbital periods from 0.9 to 2.9 days. In total, 9448 times of minimum for these binaries were analyzed in an attempt to identify the period variations caused by the third bodies in these systems. The well-known method of the light-travel time effect was used for the analysis. The orbital periods of the outer bodies were found to be between 1 and 14 years. This hypothesis makes such systems interesting for future prospective detections of these components, despite their low predicted masses. Considering the dynamical interaction between the orbits, the system KIC 3440230 seems to be the most interesting, in which one would expect the detection of some effects (i.e., changing the inclination) even after a few years or decades of observations.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: individual (KIC 2305372, KIC 3440230, KIC 5513861, KIC 5621294, KIC 7630658, KIC 8553788, KIC 9007918, KIC 9402652, KIC 10581918, KIC 10686876)

Supporting material: machine-readable and VO table

1. INTRODUCTION

Eclipsing binaries (EBs) provide us with an excellent method for deriving the basic physical properties of the two eclipsing components (their radii, masses, and temperatures). Moreover, they can also serve as independent distance indicators: one can study the dynamical evolution of the orbits, test the stellar structure models, or discover additional components in these systems (see e.g., Guinan & Engle 2006). On the other hand, the Kepler satellite (Borucki et al. 2010) provides us with unprecedented accuracy of photometric data. From this huge set of observations, 1879 EBs were detected after the first data release (Prša et al. 2011), which was later extended to 2165 (Slawson et al. 2011).

Such a huge database of EBs observed with superb precision and monitored continuously over a period of four years encouraged several teams to look for a periodic modulation of data, indicative of triple systems. The use of such a method and its limitations are described elsewhere (e.g., Irwin 1959, or Mayor 1990). For example, Gies et al. (2012) presented 41 suspected triples, while Conroy et al. (2014) listed 236 potential triples. More will be published in the future by J. A. Orosz (see Conroy et al. 2014). Moreover, Rappaport et al. (2013) presented 39 dynamically interesting systems, where the third-body periods are short enough (if compared with the binary period) that some interaction between the orbits is expected or even observed (e.g., changing of the inclination). On the other hand, most of the triples listed in Conroy et al. (2014) have periods of the order of hundreds or even thousands of days, so long periods were usually only estimated (due to limited coverage of the Kepler data) or were influenced by large errors.

For this reason we decided to perform a similar analysis to detect third-body signals for other systems, but based on a larger data set if available. For some of the systems we tried to observe additional ground-based observations. These were done quite recently, so even a single point can help us to better constrain the third-body period. Finally, we also tried to find photometry from other sources, like the survey data from SuperWASP (Pollacco et al. 2006), NSVS (Woźniak et al. 2004), ASAS (Pojmanski 2002), and others. These (mostly rather scattered) points help us to prove the long-term stability of the orbital period of the close pair or its evolution (e.g., the quadratic ephemeris).

2. SELECTION PROCESS FOR THE BINARIES

All the studied systems were chosen according to their remarkable variations in the $O – C$ diagrams. Such systems naturally complete a set of triple systems as presented by Gies et al. (2012) and Conroy et al. (2014). However, these two published studies only presented binaries in which the third-body variations are visible in the Kepler data set, and those with longer periodic modulation were omitted or only briefly mentioned. This is the main impact of this paper. We decided to include in our study those systems where the orbital periods of the third bodies are longer, and we also harvested for such an analysis the ground-based surveys and our new photometric data. Obviously, this also leads to the conclusion that the multiplicity fraction should be even higher than that from the previous studies because a non-negligible number of triples have a third-body orbital period of the order of years, decades, or even longer.

For the systems under our analysis we have chosen only those systems that fulfill the following criteria. All of them are Algol-type detached binaries with circular orbits. This information was taken from visual inspection of the Kepler EB catalog. All have remarkable curvatures in their $O – C$ diagrams, which was considered on the basis of the Gies et al. (2012) and Conroy et al. (2014) minimum times plotted in the

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Supporting material: machine-readable and VO table

1 http://keplerbs.villanova.edu/
$O-C$ diagrams in the $O-C$ gateway\(^5\) (Paschke & Bráť 2006). None of these systems was studied before concerning the third-body orbits (not counting a brief remark in Gies et al. 2012 with no orbital solution). For each of them some additional photometry also exists (older or more recent) besides the Kepler data. At this point it is worth mentioning that two of the analyzed systems (KIC 7630658 and KIC 9007918) were not included in the previous work on Kepler triples detected using eclipse timings by Gies et al. (2012). Therefore, we have to emphasize that due to these rather limited selection mechanisms our study does not aim to present a complete sample for any statistical analysis of Kepler EBs. As a by-product some systems were found to exhibit no visible variation or yielded rather spurious results; see below.

3. PHOTOMETRY AND LIGHT CURVE (LC) MODELING

The analysis of the LCs based on Kepler photometry was carried out using the program PHOEBE (Prša & Zwitter 2005) for all of the systems. This program is based on the Wilson–Devinney algorithm (Wilson & Devinney 1971) and its later modifications. However, some of the parameters have to be fixed during the fitting process. The limb-darkening coefficients were interpolated from van Hamme’s tables (van Hamme 1993). The albedo coefficients $A_i$, the gravity-darkening coefficients $g_i$, and the synchronicity parameters $F_i$ were also computed during the fitting process due to the high quality of the photometry. The same applies for the value of the third light, which was also considered to be a free parameter and has been fitted (in agreement with our third-body hypothesis). The temperature of the primary component was kept fixed according to the $T_1$ value as given in the Kepler catalog\(^6\) (Brown et al. 2011), while only the secondary temperature was fitted. In our final solution we only present a ratio of the temperatures $T_2/T_1$ for higher robustness due to (sometimes) problematic values of the $T_1$ from the Kepler catalog. An issue with the mass ratio was solved by fixing $q = 1$ because no spectroscopy for these selected systems exists, and for detached EBs the LC solution is almost insensitive to the photometric mass ratio (see, e.g., Terrell & Wilson 2005).

The quality of the LC fit is even noticeable by the naked eye; see Figure 1. The automatic routines as used, e.g., by Slawson et al. (2011) are definitely better for reducing huge data sets of hundreds of binaries; however, the codes sometimes produce spurious results. If we analyze this particular system in more detail, we are able to get a better fit to the data, lower residuals, and hence also parameters with lower errors. The automatic pipelines may not even compute parameters like albedos, gravity brightening, and third light. All of these parameters can also be fitted with the Kepler data and help us to obtain a better fit to the data.

However, it is necessary to admit that some of the parameters can correlate with each other during the fitting process (this especially applies for luminosity and temperature, inclination and the third light for partially eclipsing systems, etc.). This problem was avoided by checking whether or not there is a value in the correlation matrix higher than 0.8, and if so, such a fit was not accepted. Another iteration with a different parameter set was used, and all systems were analyzed this way, yielding the results presented below.

4. THE TIMES OF MINIMUM LIGHT

CCD follow-up observations of selected Kepler targets were mostly carried out at the Ondřejov Observatory in the Czech Republic (labeled as OND in the tables with minimum times), and a few new observations were also obtained remotely with the BOOTES-1A and BOOTES-2\(^7\) telescopes located in Spain (labeled as BOO-1 and BOO-2 in the tables with minimum times). The new times of primary and secondary minima and their respective errors were determined using the classical Kwee & van Woerden (1956) method or our new approach (see below). All the times of minima used for the analysis are given in the appendix Table 5.

For the analysis of minimum times and variation of the orbital period caused by the third body, one needs the minimum times to be as precise as possible. For some of the Kepler targets, the times of minima exist and were even published several times; see, e.g., Gies et al. (2012) or Conroy et al. (2014). However, their published times of minima differ significantly—sometimes more than their respective errors. One possible explanation is that the abovementioned teams included or did not include the error in the barycentric times of

\(^5\) http://var.astro.cz/ocgkate/
\(^6\) http://archive.stsci.edu/kepler/data__search/search.php
\(^7\) http://bootes.iaa.es/
the Kepler data, which was first mentioned in Kepler Data Release 19.8

For this reason, we have proceeded in the following way. First, the times of minima published by Gies et al. (2012) were taken and plotted in the O–C diagram. The same was done with the data by Conroy et al. (2014), and the O–C diagrams were analyzed to check whether some periodic modulation due to the third body was present. Then, the original data from the Kepler archive were downloaded and analyzed. Such an analysis was done in several steps. First, from the original raw files the photometry was extracted, the flux converted into magnitudes, and the individual LCs in different quarters of data were analyzed and the theoretical LCs were constructed. Let us call this Method 1. In Method 2 we used the data downloaded from the EB catalog9 by Slawson et al. (2011), which were already detrended and the normalized flux versus BJD was provided. These LCs were analyzed and used to construct the theoretical LC (but from the whole Kepler mission).

The theoretical LCs were used to derive the times of minima following the AFP method as described in Zasche et al. (2014). Using the LC templates from Method 1 and 2 and also the times of minima from Gies et al. (2012) and Conroy et al. (2014), we have four different sets of times of minima for the analysis (the disadvantage of the Gies et al. 2012 data is the fact that only a portion of the Kepler data was provided: those obtained after reducing only the first 9 quarters). These four data sets sometimes differed significantly and the best one (with the lowest scatter) was used for the subsequent analysis of a particular system. Usually, the best one was the data set obtained using Method 2.

However, it is natural that some of the limitations of the method play a role. The most critical issue is the fact that for deriving the times of minima we always use the same LC template. However, in some cases the shape of the LC varies during the Kepler mission and the difference is sometimes visible even by the naked eye (see comments below for particular systems). This problem can be avoided using the different LC templates for data obtained during the different time epochs. However, it is questionable whether using five or a hundred different LC templates for the whole Kepler data set would provide a better result. Hence, we solved this problem using a slightly different template for each Kepler quarter.

If we compare both minimum derivation methods, we find some aspects of the problem. The classical Kwee & van Woerden (1956) method was used only for recent observations due to the fact that only small parts of the minima were observed and the whole LC cannot be fitted. On the other hand, the AFP method can provide us with a much more precise result even with a lower number of observations, but one needs the complete LC template, and hence the complete observed LC. Generally, the individual errors from the AFP method are a bit lower (but not 10 times lower) than the classical errors from the Kwee & van Woerden (1956) method and are not affected by any observational biases, incorrect reductions, poor conditions, etc. as can be true for the ground-based ones.

5. THE PERIOD CHANGES

For the analysis of period changes in these binaries, we used a well-known method introduced by Irwin (1959). It resulted in a set of parameters of the third-body orbit: the period of the third body $P_3$, eccentricity $e$, semi-amplitude of the variation $A$, time of periastron passage $T_0$, and longitude of periastron $\omega$. The input values for the analysis were the ephemerides (HJD$_0$, $P$) given by Slawson et al. (2011), and these ephemerides were also recomputed. If necessary, the quadratic term of the ephemerides was also used (attributed to the mass transfer between the components). The solutions presented below were found using Monte Carlo simulations and the simplex algorithm. However, the individual errors of the parameters are taken from the code and may be too optimistic for some of the systems.

All the new precise CCD times of minima from the Kepler satellite were used with a weight of 10 in our computation; some of the less precise measurements were weighted by a factor of five, while the poorly covered minima were given a weight of 1. This applies mostly for the minimum times derived from other sources of photometry (like ASAS, SuperWASP, etc.), which were derived using the same method as the Kepler ones, but using a different LC template. The weights were used instead of the uncertainties due to the fact that for the older published minima any information about their accuracy is missing.

Because we only studied the period changes due to the third-body orbit and all of the systems are circular, for most of the systems only the deeper (primary) minimum was used to detect the period changes.

6. INDIVIDUAL SYSTEMS

In the following section we present the results of our analysis for all of the systems. The whole procedure is described in detail for the first binary, and the others are only briefly discussed due to the similarity of the analysis to the first one. Table 1 summarizes basic information about the stars, their cross-identification, magnitudes, and photometric indices. As one can see from the $(J–H)$ index, most of the stars are of F and G spectral type.

6.1. KIC 2305372

The first system in our sample is the star KIC 2305372, which was first recognized as a variable by the Hatnet (Hartman et al. 2004) and ASAS (Pigulski et al. 2009) surveys in the pre-Kepler era. After that, it was included in the catalog of EBs in the Kepler field (Slawson et al. 2011). The times of minima were published by Gies et al. (2012) and later by Conroy et al. (2014). However, Gies et al. (2012) presented the system as a candidate triple, while Conroy et al. (2014) roughly estimated a period of about 3700 days. No spectral analysis was carried out, and hence we can only estimate that it is probably a system of G spectral type (from the $J–H$ photometric index).

The LC analysis was carried out from the Kepler detrended data, and its parameters are given in Table 2. As one can see, both components are rather different, and no third light was detected during the LC solution. The final LC fit is presented in Figure 2, where the shape of the LC is clearly seen to be a classical Algol shape. However, the LC shape seems to be slightly asymmetric (see the outside-eclipse curvature). This LC template was also used to derive the times of minima (using

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8 https://archive.stsci.edu/kepler/release_notes/release_notes19/DataRelease_19_20130204.pdf
9 keplerbvs.villanova.edu/
### Table 1

| System    | Other ID          | R.A.    | Decl.   | $KEP_{max}$ | $(J-H)$ (mag) | $(B-V)$ (mag) | Sp. Type |
|-----------|-------------------|---------|---------|-------------|---------------|---------------|-----------|
| KIC 2305372 | 2MASS J19275768+3740219 | 19°27′57″ | +37°40′21″ | 13°82       | 0.364         | ...           | ...       |
| KIC 3440230 | 2MASS J19215310+3831428 | 19°21′53″ | +38°31′42″ | 13°76       | 0.317         | ...           | ...       |
| KIC 5513861 | TYC 3123–2012–1   | 18°57′24″ | +40°42′52″ | 11°76       | 0.238         | 0.448         | W8V       |
| KIC 5621294 | 2MASS J19285262+4053359 | 19°28′52″ | +40°53′36″ | 13°76       | 0.143         | ...           | ...       |
| KIC 7630656 | 2MASS J19531365+4315224 | 19°51′59″ | +43°15′22″ | 13°89       | 0.389         | ...           | ...       |
| KIC 8553788 | 2MASS J19174291+4438290 | 19°17′42″ | +44°38′29″ | 12°69       | 0.120         | 0.537         | A7V       |
| KIC 9007918 | TYC 3541–2296–1   | 19°04′02″ | +45°21′21″ | 11°66       | 0.135         | 0.155         | F5IV      |
| KIC 9402652 | V2281 Cyg        | 19°25′06″ | +45°56′03″ | 11°82       | 0.154         | 0.470         | F8V       |
| KIC 10581918 | WX Dra           | 18°52′10″ | +47°48′16″ | 12°80       | 0.186         | ...           | ...       |
| KIC 10686876 | TYC 3562–961–1   | 19°56′13″ | +47°54′33″ | 11°73       | (−0.041)      | 0.204         | F0V       |

Notes:

- a **Kepler** database.
- b 2MASS catalog; Skrutskie et al. (2006).
- c Based on the Tycho catalog; Pickles & Depagne (2010).

### Table 2

| System    | $T_2/T_1$ | $i$ (deg) | $\Omega_1$ | $\Omega_2$ | $L_1$ (%) | $L_2$ (%) | $L_3$ (%) |
|-----------|-----------|-----------|-------------|-------------|-----------|-----------|-----------|
| KIC 2305372 | 0.6637 (0.0152) | 79.92 (0.27) | 5.431 (0.035) | 4.134 (0.059) | 82.70 (0.90) | 17.30 (0.80) | 0         |
| KIC 3440230 | 0.6082 (0.0085) | 81.63 (0.82) | 6.278 (0.69)  | 5.114 (0.192) | 87.02 (0.83) | 12.98 (0.47) | 0         |
| KIC 5513861 | 0.9891 (0.0115) | 79.37 (0.08) | 5.393 (0.012) | 5.773 (0.024) | 55.10 (0.23) | 43.97 (0.27) | 0.94 (0.55) |
| KIC 5621294 | 0.5620 (0.0096) | 72.32 (0.73) | 4.182 (0.084) | 4.255 (0.106) | 82.85 (0.35) | 8.86 (3.02)  | 11.29 (0.99) |
| KIC 7630656 | 0.9635 (0.0004) | 79.76 (0.02) | 7.660 (0.005) | 7.646 (0.007) | 51.66 (0.02) | 43.26 (0.02) | 5.07 (0.02)  |
| KIC 8553788 | 0.6385 (0.0022) | 69.72 (0.22) | 5.351 (0.025) | 5.106 (0.057) | 80.15 (0.71) | 13.27 (0.15) | 6.56 (0.60)  |
| KIC 9007918 | 0.6289 (0.0008) | 78.83 (0.05) | 5.479 (0.006) | 5.781 (0.016) | 79.06 (0.05) | 6.36 (0.02)  | 14.58 (0.05) |
| KIC 9402652 | 0.9956 (0.0033) | 79.61 (0.07) | 4.386 (0.007) | 4.357 (0.004) | 50.01 (1.68) | 49.99 (1.44) | 0         |
| KIC 10581918 | 0.6813 (0.0126) | 88.53 (0.42) | 5.595 (0.058) | 5.751 (0.050) | 86.68 (0.67) | 13.32 (0.50) | 0         |
| KIC 10686876 | 0.6532 (0.0048) | 88.35 (0.06) | 6.976 (0.030) | 16.290 (0.123) | 92.32 (3.41) | 2.76 (0.11)  | 4.92 (3.08)  |

The method as described above. For the period analysis we collected the Hatnet, ASAS, SuperWASP, and Kepler data points and derived more than 800 times of primary minima for this star. One new minimum was also observed by the authors at Ondřejov Observatory in the Czech Republic.

This data set was analyzed and the method of Irwin (1959) was used. The results are given in Table 3 and the final fit is also plotted in Figure 3. In these plots only the new post-Kepler data and the isolated measurements (groups of up to three data points) are plotted with their respective error bars for clarity. Plotting the error bars for all the data would diminish the readability of the graphs (however, for some observations their respective error bars are too small and are plotted almost inside the individual dots). We are aware of the fact that only a few poor-quality points define the shape of the third-body variation and its period $P_3$ in the $O - C$ diagram. However, the parabolic fit is not able to describe the data in such detail. From the parameters of the third body one is also able to compute the mass function of the third body in the system, which is also given in Table 3. As one can see, its value is rather high, so the third component should also be detected in the LC solution as a third light contribution. However, no such value was detected during the LC fitting. This still remains an open question; however, we also have to mention that the shape of the LC varies over time and the LC fit in different quarters of the data differs a bit. This can also influence our result and the minimum precision, LC modeling, and third light detection. Regrettably, with no information about the masses of the eclipsing components, one cannot easily set a tighter limit to the mass of the predicted third body.

#### 6.2. KIC 3440230

KIC 3440230 was discovered by Lawson et al. (2011), and later Gies et al. (2012) included the star in the group of tertiary candidates. However, there was also a remark about the flux variation and possible pulsations (Gies et al. 2012). This is the star with the longest orbital period in our sample.

The same method as for the previous star was used. We were not able to fit the outside-eclipse curvature of the Kepler LC (due to asymmetry of the LC), but the primary minimum was fitted pretty well. Therefore, the LC template was used to derive the minimum times used for a subsequent period analysis. Besides the Kepler data, a few SuperWASP minima were also derived. However, these were not used in the analysis due to their large scatter. The long-term period decrease is also visible in the Kepler data with no need to spread the time interval with these scattered data points. From the third-body orbit fitting there resulted a very small mass function value

$$f(m_3) = \frac{(m_3 \sin i)^3}{(m_1 + m_2 + m_3)^2}$$

$$= \frac{1}{P_3^2} \cdot \left[ \frac{173.15 \cdot A}{\sqrt{1 - e^2 \cos^2 \omega}} \right]^3,$$
Figure 2. *Kepler* light curves of all studied systems. The red curves show the final fit, and the dots show the observations.
The Parameters of the Third-body Orbits for the Individual Systems

| System          | HJD₉ (2450000+) | P (days) | A (deg) | ω (deg) | Pₐ (year) | T₀ [HJD] (2400000+) | e | f (m₃) | P²ₑ/P² (M₂) |
|-----------------|-----------------|----------|---------|---------|-----------|---------------------|---|---------|-------------|
| KIC 2305372     | 4965.9539 (8)   | 1.4047173 (15) | 0.0211 (13) | 86.9 | 10.36 (0.16) | 54532 (62) | 0.625 (66) | 0.5453 (18) | 27919        |
| KIC 340230      | 5687.5150 (3)   | 2.8811052 (38) | 0.0006 (25) | 111.3 | 1.04 (0.13)  | 55818 (32) | 0.264 (98) | 0.0010 (1)  | 137          |
| KIC 5513661     | 4955.0004 (9)   | 1.5102096 (10) | 0.00831 (73) | 27.2 | 7.94 (0.18)  | 56347 (139) | 0.135 (89) | 0.0861 (39) | 8540         |
| KIC 5621294     | 4954.5109 (2)   | 0.9389102 (3)  | 0.00024 (5) | 133.9 | 2.70 (0.10)  | 56124 (28) | 0.654 (175) | 0.000014 (2) | 2843         |
| KIC 7630658     | 1.8018668       | 2.8811052 (38) | 0.0006 (25) | 111.3 | 1.04 (0.13)  | 55818 (32) | 0.264 (98) | 0.0010 (1)  | 137          |
| KIC 2305372     | 4965.9539 (8)   | 1.4047173 (15) | 0.0211 (13) | 86.9 | 10.36 (0.16) | 54532 (62) | 0.625 (66) | 0.5453 (18) | 27919        |
| KIC 340230      | 5687.5150 (3)   | 2.8811052 (38) | 0.0006 (25) | 111.3 | 1.04 (0.13)  | 55818 (32) | 0.264 (98) | 0.0010 (1)  | 137          |
| KIC 5513661     | 4955.0004 (9)   | 1.5102096 (10) | 0.00831 (73) | 27.2 | 7.94 (0.18)  | 56347 (139) | 0.135 (89) | 0.0861 (39) | 8540         |
| KIC 5621294     | 4954.5109 (2)   | 0.9389102 (3)  | 0.00024 (5) | 133.9 | 2.70 (0.10)  | 56124 (28) | 0.654 (175) | 0.000014 (2) | 2843         |

which is mostly caused by the small amplitude of the variation. The potential third body would probably be a late-type dwarf star.

On the other hand, what makes this system the most interesting is the fact that the period $P₁$ is rather short, and hence one can hope to detect some dynamical interaction between the orbits (see, e.g., Söderhjelm 1975; Rappaport et al. 2013). The nodal period can be computed from the equation

$$P_{nodal} = \frac{4}{3} \left( 1 + \frac{m₁ + m₂}{m₃} \right) \times \frac{P²ₑ}{P} (1 - \varepsilon) / \sqrt[3]{\frac{C}{G₂ \cos j}},$$

where the subscripts 1 and 2 stand for the EB components and 3 stands for the third distant body, the term $G₂$ stands for the angular momentum of the wide orbit, $C$ is the total angular momentum of the system, and $j$ stands for the mutual inclination of the orbits. For this system the ratio of periods $P²ₑ/P$ resulted in a surprisingly low value of only about 137 years. Hence, one can hope to detect some changes in the binary orbit even after a few years of observations. The most promising is the inclination change, because it is rather easily detectable. Due to its deep eclipses a change in the inclination angle should also be detected in ground-based data of modest quality. However, the amplitude of any such change is also strongly dependent upon a third-body mass and the orientation of its orbit. For the derivation of these quantities, precise interferometry or spectroscopy would be very useful. However, one cannot hope to obtain these observations easily for a 14 mag star.

### 6.3. KIC 5513861

The star KIC 5513861 (also TYC 3123-2012-1) was first mentioned as a variable by Pigulski et al. (2009) from the ASAS data. Later, Gies et al. (2012) reported its curvature in the $O − C$ diagram, which was probably caused by a third body. Also mentioned were the pulsations and rapid flux variability. Conroy et al. (2014) published preliminary results from the Kepler data estimating that the third body should have a period of $\approx 1800$ days. This is the first system in our sample of stars, which was included in the work by Pickles & Depagne (2010), who used Tycho photometry for estimating the spectral type of the star; see Table 1.

The same approach was used for the analysis: the LC was fitted and the final plot was then used as a template to derive the precise times of minima. The final $O − C$ diagram is plotted in Figure 3, where some minima as derived from the ASAS (Pojmanski 2002) and SuperWASP (Pollacco et al. 2006) surveys were also included together with our three new observations (one from Ondřejov Observatory in the Czech Republic, two from the BOOTES-1A and BOOTES-2 telescopes in Spain). All of the data clearly define the third-body variation with a period of about 6 years and yield a moderate value of the mass function. However, the fraction of the third light is rather lower than anticipated from the third-body mass function. With the available data we are not able to find the problem, and the nature of the third body still remains an open question.

### 6.4. KIC 5621294

The system KIC 5621294 was discovered from the Kepler data (Lawson et al. 2011). Later, the times of minima were published by Gies et al. (2012), who also included a remark about a possible parabolic trend in the $O − C$ diagram, starspots, and pulsations.

The LC was fitted and analyzed, resulting in the largest difference between the primary and secondary temperatures of the eclipsing components in our sample of stars. From the LC parameters in Table 2 one can see a non-negligible value of the third light and only a very weak contribution of the secondary component to the total light. On the other hand, the times of minima as derived from the Kepler data show a significant period decrease (described via parabolic ephemerides); see Figure 3. Moreover, superposed over the parabola, a small periodic variation is also visible, with period of about 2.7 years and the lowest amplitude in our sample (only about 21 s); see Figure 4. This small amplitude also yielded a small value of the predicted third light value, and hence a third light contribution as detected during the LC solution should probably be attributed to another body in the system or a close visual component. However, it is still rather premature to speculate that we are dealing with a real quadruple system. Such a low amplitude of the variation in the $O − C$ diagram could also serve as a test example of what can be discovered from the Kepler data using these classical techniques with EBs: assuming component masses $M₁ = M₂ = 1M_☉$, then the
minimum third-body mass (i.e., assuming \(i = 90^\circ\)) resulted in \(M_{3,\text{min}} = 0.039 M_\odot\), a typical brown dwarf mass.

6.5. **KIC 7630658**

The system KIC 7630658 was discovered by Slawson et al. (2011) from the *Kepler* data. No other analysis was carried out and our knowledge about the system is very limited. It is the faintest star in our sample.

The shape of the LC as obtained by the *Kepler* satellite clearly shows two well-defined minima, and hence the derivation of the times of minima was rather straightforward. The final parameters are given in Table 2, where one can see that both components are similar to each other and only a small fraction of the third light was detected. Variation with a period of about 2.5 years is clearly visible in the data; however, our last observation slightly deviates from the prediction. This can be caused by long-term modulation of the orbital period.
after several decades of observations.

6.6. KIC 8553788

The star KIC 8553788 was first mentioned as an EB by Pigulski et al. (2009). Later, only the results from the Kepler data analysis were published: Slawson et al. (2011), Prša et al. (2011), and Gies et al. (2012). The latter paper gives some information about possible pulsations, starspots, and a possible third body. This system seems to be of the earliest spectral type in our sample of stars (see Table 1).

Our analysis using the Kepler data yielded an LC solution showing that the primary is the dominant object in the system, and hence only the primary minima were used for the $O-C$ diagram analysis. The nine-year variation is clearly visible in the plot despite the fact that the orbital period is still determined only by the last observation from the Ondřejov Observatory. The older observations from the ASAS and SuperWASP surveys only slightly follow the predicted fit, but have quite a large scatter. Our fit of the minimum times yielded a rather high value of eccentricity; however, the minimal third-body mass as resulted from the mass function is somewhat lower than the masses of the eclipsing components. Its light contribution hence should probably be higher than resulted from our LC fit.

6.7. KIC 9007918

The star KIC 9007918 (also TYC 3541-2296-1) was first detected as a variable by Devor et al. (2008) on the basis of the TRES survey data. Later, the star was included in the catalog of Kepler EBs (Slawson et al. 2011; Prša et al. 2011).

Some variations were detected in the LC during the Kepler mission, and the whole LC is not perfectly symmetric. This can also play a role in the precision of the derived times of minima from the LC template. As one can also see from the LC, the secondary minimum is very shallow, and hence we used only the primary ones to analyze the period changes in this binary. Together with the old (and rather scattered) photometry from the TRES survey we were able to detect periodic variations with a period of about 1.3 years and an amplitude of only about 41 s. The other interesting issue is the value of the period for a possible dynamical interaction between the orbits of $P_2/P \sim 445$ years. Hence, we can hope to find some changes after several decades of observations.

6.8. KIC 9402652

The star KIC 9402652 (also V2281 Cyg) was already discovered as a variable in the pre-Kepler era and a few observations of the minima of this star were published. It was mentioned in the list of stars observed by the ROTSE survey (Diethelm 2001), Pigulski et al. (2009) later included the star in their ASAS observations of the Kepler fields, and the times of minima were published by Gies et al. (2012) and Conroy et al. (2014).

As one can see, the system consists of two almost identical stars with practically the same temperatures and luminosities. For this reason, both minima are also very similar, and hence both the primary and secondary were used for the period analysis. We also collected the older published minima together with the photometry from the NSVS, SuperWASP, and ASAS surveys. Thanks to the large data set of available times of minimum observations, this system seems to be the richest one in our sample of stars (and with the data coverage ranging over more than 15 years). The $O-C$ diagram together with our new observations clearly show a four-year variation, but with rather high eccentricity.

6.9. KIC 10581918

The system KIC 10581918 (also WX Dra) was discovered to be a variable as early as 1960 by Tsesevich (1960). Since then a few observations of the minima were published, but no LC nor spectroscopic analysis of the system. Due to a very deep primary eclipse of this star (1.67 mag), the older visual and photographic observations can also be reliable in the analysis of the period changes. The very first preliminary results were recently published in conference proceedings (Wolf et al. 2015).

As one can see from the results of our analysis, the period of the third body is of about 14 years (the longest one in our sample) and is now well covered, but its amplitude is only poorly defined with our data. New minimum time observations in the upcoming years can help us to better derive the amplitude of variations. However, the predicted mass function of the third body resulted in a rather low value, and hence a non-detection of the third light in the LC solution is also something to be expected.

6.10. KIC 10686876

The EB KIC 10686876 was first mentioned by Devor et al. (2008) based on the TRES survey data. Later, the star was included in the Kepler EB database, Prša et al. (2011), and Slawson et al. (2011). Gies et al. (2012) published the minimum times for the system, but no other information or analysis was obtained or performed.

The star seems to be the only system in our sample that shows a total eclipse. For this reason the error of the inclination from the LC fit is already very small. On the other hand, the secondary component is probably a very small star and the primary is the dominant one. As one can also see, the primary eclipses are rather deep and provide us with much better times of minima than the secondaries. Hence, analyzing the available minima from Kepler, TRES, SuperWASP, and our new data (two from Ondřejov and two from the BOOTES-1A and BOOTES-2 telescopes in Spain), we obtained a set of third-body parameters given in Table 3 and the final fit presented in Figure 3. The variation with a period of about 6.7 years is now clearly visible in the current data set, and the shape of the $O-C$ variation should easily be confirmed and the parameters improved by a few new observations obtained during the upcoming years.
7. DISCUSSION AND CONCLUSIONS

Ten selected binaries were found to be worth studying due to the presence of the distant components, which cause a periodic modulation of their eclipsing periods. The periods of the third bodies (from 1 to 14 years) are usually adequately covered by the Kepler and ground-based data, so the variation is certain nowadays. However, its origin is still questionable in several cases. This especially applies to systems where the predicted mass function of the third body and the non-detected third light from the LC solution contradict each other. However, this could be caused by the following reasons: (1) an imperfect LC fit (for those binaries with slightly asymmetric LCs), (2) not very well-defined third-body variation in the O–C diagram (especially in those cases where the variation is mostly determined by the older scattered ground-based data), (3) the variation in the O–C diagram being incorrectly described (i.e., missing a quadratic term or a fourth-body variation), (4) an exotic object as the distant body (or also as a binary, hence having a much lower luminosity), or (5) some other phenomena modulating the period variation in the O–C diagram (such as magnetic or other activity of the components). As a by-product of our analysis, we found a few more systems where the O–C variation was not found, or is still questionable. These are summarized in Table 4. Regrettably, this sample is still too limited to do a reliable statistical analysis of the incompleteness of triple systems found in the Kepler data.

At this point it would be useful to mention that when using Method 1 as introduced in Section 3, some of the systems also have short-cadence data in the Kepler photometric database. Using the short-cadence data produces a much more precise minimum derivation (these minimum times are labeled as “Kepler SC” in Table 5), but can also reveal some other phenomena that are not detectable in the long-cadence data. This happened for KIC 8553788 and KIC 10686876, for which short time variation was detected in the short-cadence data (probably δ Scuti pulsations) that was not visible in the long-cadence data. However, such additional variation also influences the LC fitting and its precision.

One also has to consider the limitations of the method used for the analysis. The LC fit is a crucial issue because it is used to derive the minimum times for a subsequent analysis. However, the LC fits can also be a problematic issue because we are dealing with pure photometry with no information about the individual masses of the components. Hence, fixing the mass ratio value to \( q = 1 \) is in fact only the first rough simplification. Therefore, with no information about the individual masses, the mass function of the third body provides only very preliminary information about such objects. For this reason and because of the unknown distance, the angular separation of the third component cannot be computed for a prospective interferometric detection. However, it should

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Table 4
Other Analyzed Systems

| System       | Other ID | Remark                                           |
|--------------|----------|--------------------------------------------------|
| KIC 04245897 | V583 Lyr | some variation with period about 50 years found, but based only on older photographic data |
| KIC 06187893 | TYC 3128-1653-1 | quadratic ephemerides or third body with long period, not very convincing, new data needed |
| KIC 06852488 | 2MASS J19135355+422482 | some variation detected, but period still uncertain, more data needed |
| KIC 07259889 | 2MASS J18510630+4248400 | some variation found, but showing rather non-periodic modulation |
| KIC 07938468 | V481 Lyr | quadratic ephemerides based also on older photographic data |
| KIC 08552540 | V2277 Cyg | no variation found |
| KIC 09101279 | V1580 Cyg | some variation found, but not very convincing, older data too scattered |
| KIC 09602595 | V0995 Cyg | variation with period 13.3 years found, but the data before 1970 are in contradiction |
| KIC 09899416 | V1238 Cyg | no variation found |
| KIC 10736223 | V2290 Cyg | quadratic ephemerides only, based on older visual data |
| KIC 11913071 | V2365 Cyg | no variation found |
| KIC 12071006 | V379 Cyg | some variation detected only on the Kepler data, older measurements too scattered |

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Table 5
List of the Minimum Timings Used in the Analysis

| Star               | BJD---2400000 | Error (day) | Type | Filter* | Source / Observatory |
|--------------------|---------------|-------------|------|---------|----------------------|
| KIC 2305372        | 52802.67112   | 0.08710     | Prim | I       | Hatnet               |
| KIC 2305372        | 52806.88251   | 0.07516     | Prim | I       | Hatnet               |
| KIC 2305372        | 52809.68474   | 0.02068     | Prim | I       | Hatnet               |
| KIC 2305372        | 52813.90357   | 0.06025     | Prim | I       | Hatnet               |
| KIC 2305372        | 52816.71288   | 0.02019     | Prim | I       | Hatnet               |
| KIC 2305372        | 52820.92775   | 0.03789     | Prim | I       | Hatnet               |
| KIC 2305372        | 52823.74173   | 0.04552     | Prim | I       | Hatnet               |
| KIC 2305372        | 52827.95039   | 0.03124     | Prim | I       | Hatnet               |
| KIC 2305372        | 52830.76181   | 0.10454     | Prim | I       | Hatnet               |
| KIC 2305372        | 53986.89162   | 0.00559     | Prim | I       | ASAS                 |
| KIC 2305372        | 54349.28814   | 0.00479     | Prim | I       | ASAS                 |
| KIC 2305372        | 54232.70365   | 0.04672     | Prim | W       | SuperWASP            |

Notes:
* W and K stand for the special filters used for SuperWASP and Kepler.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.)
probably be hard to detect such bodies due to the relative faintness of most of the stars using this technique. To conclude, only dedicated high-dispersion, high signal-to-noise ratio spectroscopic observations and a subsequent analysis can tell us something more about these objects and reveal their true nature. Moreover, new photometric observations in the upcoming years would be of great benefit, especially in systems where the period variation is still not very certain and for the dynamically interesting systems like KIC 3440230.

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To conclude, only dedicated high-dispersion, high signal-to-noise ratio spectroscopic observations and a subsequent analysis can tell us something more about these objects and reveal their true nature. Moreover, new photometric observations in the upcoming years would be of great benefit, especially in systems where the period variation is still not very certain and for the dynamically interesting systems like KIC 3440230.

APPENDIX

TABLES OF MINIMA

Table 5 presents the times of minimum light for all of the analyzed systems.

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