

Candidates of eclipsing multiples based on extraneous eclipses on binary light curves: KIC 7622486, KIC 7668648, KIC 7670485 and KIC 8938628

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Abstract Four candidates of eclipsing multiples, based on new extraneous eclipses found on *Kepler* binary light curves, are presented and studied. KIC 7622486 is a double eclipsing binary candidate with orbital periods of 2.2799960 d and 40.246503 d. The two binary systems do not eclipse each other in the line of sight, but there is mutual gravitational influence between them which leads to the small but definite eccentricity of 0.0035(0.0022) associated with the short 2.2799960 d period orbit. KIC 7668648 is a hierarchical quadruple system candidate, with two sets of solid 203 ± 5 d period extraneous eclipses and another independent set of extraneous eclipses. A clear and credible extraneous eclipse is found on the binary light curve of KIC 7670485 which makes it a triple system candidate. Two sets of extraneous eclipses with periods of about 390 d and 220 d are found on KIC 8938628 binary curves, which not only confirm the previous conclusion of the 388.5 ± 0.3 triple system, but also indicate new additional objects that make KIC 8938628 a hierarchical quadruple system candidate. The results from these four candidates will contribute to the field of eclipsing multiples.

Key words: binaries: eclipsing — techniques: photometric — methods: observational

1 INTRODUCTION

Multiple stellar systems are interesting, and circumbinary planets are also attractive. They have varying and changing spatial structure, which exhibits particular physical phenomena that binaries or single stars cannot; extraneous eclipses, that we study in this paper, are an example. The formation and evolution of binaries depend greatly on the companion bodies around them. Close binaries need outer bodies to extract angular momentum through Kozai cycles with tidal friction (KCTF) (Kiseleva et al. 1998; Eggleton & Kiseleva-Eggleton 2001; Fabrycky & Tremaine 2007) to shrink and become as close as observed. So, knowledge of binaries cannot be complete without finding out more about their various environments.

More and more observations have demonstrated that binaries are often affiliated with multiples. Faherty et al. (2010) think that the ratio of triples to binaries is 3/5 and

quadruples to binaries is 1/4. The statistics by Tokovinin et al. (2006) show that the fraction of spectroscopic binaries with additional companions is 96% for a period of less than 3 d and 34% for a period larger than 12 d. Pribulla & Rucinski (2006) concluded that contact binary stars exist in multiple systems with a firm lower limit of $42\% \pm 5\%$. The result of D'Angelo et al. (2006) is consistent with the hypothesis that all close binaries are in triple systems. Rucinski et al. (2007) contributed evidence that close companions are very common for very close binaries with a period of less than 1 d. Not only close binaries, but wide binaries also commonly have companions. Law et al. (2010) conclude that the fraction of multiples in wide M dwarf binaries is $45^{+18\%}_{-16\%}$.

In terms of theory, Fabrycky & Tremaine (2007)'s model that included KCTF supported most or all short-period binaries having distant companions. Reipurth & Mikkola (2012) demonstrated that, through N-body simulations of their dynamical evolution, the widest bina-

ries can be reasonably formed from triple systems on timescales of millions of years. All these researches remind us that, for all kinds of binaries, additional companions are very common or even always present.

There are different methods to find multiple systems (Rappaport et al. 2013), and the method we used is searching for extraneous eclipses, which is different from those associated with binaries themselves. This method has been successfully applied to *Kepler* data. KOI-126 (Carter et al. 2011) and HD 181068 (Derekas et al. 2011) are good examples, and 10 circumbinary planets (CBPs) were found by this method (Welsh et al. 2015). In this paper, we present four multiple system candidates. Three of the candidates are presented with new extraneous eclipses, and the other, KIC 7622486, is analyzed with new vision.

The data used as the basis of this study came from the *Kepler* mission (Borucki et al. 2010; Koch et al. 2010; Caldwell et al. 2010), which had the purpose of searching for exoplanets. As a byproduct, *Kepler* provided a large amount of binary light curves, which have greatly improved the process of searching for binaries in its field. Thanks to this source of long-term, continuous and high-precision data, new discoveries which could not be made before were published gradually. For example, all the credible CBPs have been found based on *Kepler* data. The long-term continuous changes in the depths of binaries have been seen clearly from *Kepler* data (e.g. KIC 7670617; KIC 8023317, Borkovits et al. (2015). Based on *Kepler* data, Rappaport et al. (2013) and Borkovits et al. (2015) showed clear periodic variation in $O - C$ curves over several cycle lengths, and also provided good fittings based on new techniques. They obtained a large number of credible parameters of 65 triple systems, which advanced period analysis of binaries, as well as of multiple systems, both observationally and in terms of modeling.

We search for multiple candidates through looking for extraneous eclipses on the *Kepler* binary light curves. Different types of curves, including fragments of curves, long-term curves, phase curves and curves that come from removing a component of the binary, are examined visually for all the associated binary objects. The analysis method will be introduced in Section 2. The candidates found are analyzed one by one in alphabetical order in Section 3. All the candidates are analyzed by the model of a binary light curve to obtain parameters. The last section provides a summary and discussion.

2 DATA PREPARATION

2.1 Data Acquisition

All the light curve data in this paper are acquired from the Mikulski Archive for Space Telescopes (MAST)¹, in the form of a convenient compression package by the *Kepler* binary team. Data from the 2015 October 27 version were used. However, the data on objects KIC 7668648 and KIC 8938628 used here are from an older version from 2014 August 1. This is because we found that more noises were erased in the new version, which was good but unfortunately, some real eclipse signals were also erased or reduced in the process. For KIC 7668648 and KIC 8938628, data from the older version provided more effective information. The Kepler Eclipsing Binary Catalog (Prša et al. 2011; Slawson et al. 2011; Matijevič et al. 2012; Conroy et al. 2014) was also acquired from MAST, and this catalog provides the essential basis and guidance for our works. The catalog provides more than one period for some binary objects, which itself implies the existence of extraneous eclipses on the binary light curves. All the period values in this paper are from the catalog.

2.2 Data Normalization

The data used are the Pre-Search Data Conditioning (PDC) flux, the purpose of which is ‘to identify and correct flux discontinuities that cannot be attributed to known spacecraft or data anomalies’ (Kepler Data Processing Handbook²; Fraquelli & Thompson 2014). Nevertheless, PDC fluxes are not the final data that can be analyzed directly. The main problems are the discontinuities quarter to quarter and false long-term (months or longer) variations.

Hence in order to analyze light curves of the binary (or tertiary or higher) eclipse component, all the data of each object were divided into dozens of segments, normalized for each segment and stitched together into a whole for later analysis. The segmentation point on the light curves depends on the time interval between adjacent data points. If the time interval is larger than one day (somewhat arbitrarily), the light curves will be split at that gap. Therefore the data from different quarters were split naturally. After segmentation, the light curve of each segment was fitted by a cubic polynomial model, and the

¹ <http://archive.stsci.edu/>

² http://archive.stsci.edu/kepler/manuals/KSCI-19081-001_Data_Processing_Handbook.pdf

data were divided by the fitted values to get the normalized or flattened data. During the polynomial fitting, the jump points (e.g. the deep eclipse points, the flare points and the high dispersion points) were eliminated to obtain a better fitting. The points with fitting residuals larger than three times the standard deviations of fitting were removed, and then light curves were refitted. If high dispersion points still existed, they were removed before another refitting until all the high dispersion points were removed. (In practice the number of iterations is limited to 10).

This normalization process eliminated the jumps which occur segment to segment (including quarter to quarter), and also eliminated part of the long term variations. These variations may be caused by the instruments or may also be real variations. Elimination of the long term variation will not be harmful to, but on the contrary be conducive to, the analysis of short term eclipse light curves.

2.3 Phase Data Calculation

The phase light curves are needed for objects in the analysis. The calculation of phase data is as follows: 1. For the period of very small changes, a single reference epoch and period are used to calculate the phase data, and then the phase data are folded into the range of 0 to 1. For a period that shows large changes, the single reference epoch will lead to misalignment of different eclipses, or lead to an inaccurate phase value of the secondary minimums (because its adjacent primary minimum is not strictly at an integer phase). In order to cope with this situation, the minimum time of each eclipse is used as its own reference epoch to calculate the phase values (of course the minimum time of each eclipse needs to be measured previously), so phase curves with a high degree of coincidence for eclipses are obtained. 2. The range of 0 to 1 is equally divided into small segments (e.g. 200 segments per unit phase). For each segment, the folded phase data obtained from step 1 are averaged into a single value (the points with large deviations are eliminated before the average). Then all the average values constitute the merged phase curve. The phase curves in this paper, if they have special properties, always use this kind of binned phase curve. 3. In many cases, the eclipse is very sharp compared to other parts. In order to display its profile clearly, the segments at the eclipses need to be denser than other parts (e.g. 10 000 segments per unit phase). In the analysis of binary modeling, these nonuniform phase

data are also employed because the light curves on the eclipse part are much more important in the modeling and deserve much more weight.

2.4 Binary Light Curve Analysis

The binary phase light curves of the objects below were analyzed using the Wilson-Devinney program (Wilson & Devinney 1971; Wilson 1979, 1990; Van Hamme & Wilson 2007; Wilson 2008; Wilson et al. 2010; Wilson 2012). All the temperatures of the primary stars are taken from the catalog of temperatures for *Kepler* eclipsing binary stars by Armstrong et al. (2014). In the analysis, exponents in the bolometric gravity brightening law g and the bolometric albedos A for reflection heating and re-radiation on stars depend on the temperatures, such that $g = 1$ and $A = 1$ for temperatures higher than 7200 K, and $g = 0.32$ and $A = 0.5$ for lower temperatures. In this case, the 7200 K is designated as the boundary of radiative and convective envelopes. The logarithmic law for limb darkening is used, and the coefficients are internally computed in the program as a function of T_{eff} , $\lg g$ and $[M/H]$ based on the van Hamme (1993) table, where T_{eff} is from Armstrong et al. (2014) or internal iterative calculation, $\lg g$ is calculated by the orbital period and semi-major axis that are estimated assuming these are main sequence stars, and $[M/H]$ is set to be -0.2 for all objects. However, the $\lg g$ and $[M/H]$ have a very weak effect on limb darkening coefficients, so they can also have large errors.

Long-cadence *Kepler* data have a long integration time of about 30 min for each point, so this will lead to light curve smearing, especially on sharp eclipse parts. This problem is dealt with by the method of integration by Gaussian quadrature (Wilson 2012) in the Wilson-Devinney program, and the number of Gaussian abscissas when the code is executed is set to 3. However, for short-cadence data, the smearing effects are not considered since the integration time is only about 1 minute, which is short enough for our targets.

3 FOUR KEPLER BINARIES WITH EXTRANEIOUS ECLIPSES

3.1 KIC 7622486

Prša et al. (2011) and Slawson et al. (2011) give the earliest identification and light curve analysis for the object KIC 7622486, classifying it as a detached binary system. However, Borucki et al. (2011) analyzed it and

found a very probable false positive result for planetary candidates with two planets. Walkowicz & Basri (2013) and Burke et al. (2014) obtained its properties and parameters based on an assumed model of planetary candidates. Rowe et al. (2014) flagged the object as a false-positive or false alarm in their paper, Validation of Kepler’s Multiple Planet Candidates.

According to the shape of the light curves, it is suggested that the object KIC 7622486 is a quadruple system consisting of two pairs of stellar binaries. This object clearly has two sets of eclipses, with strict periods of 2.2799960 and 40.246503 d, see Figure 1. The folded phase curve of a 2.2799960 d period is shown in the lower left panel, and it can be fitted well by a binary model with a mass ratio of 0.269(0.005), see Table 1. There are twists on the two sides of the secondary eclipse (about 0.45 and 0.55 in phase), both in the observational data and the theoretical light curve, which can be seen more clearly in the small inset panel within the lower left panel. The two twists are actually the boundaries of the secondary eclipses. The agreement shown by this small detail strengthens the reliability of the stellar binarity result with a 2.2799960 d period. The more massive component star, with a much bigger radius compared to the less massive one, strongly deviates from being a sphere due to mutual gravity between the two components (see the radius of star 1 in different directions in Table 1). Thus, the massive star generates great light curve variations out of the eclipses.

The second set of eclipses with a period of 40.246503 d is not considered to be the third star revolving around the 2.2799960 d binary. The reason is that if the eclipses of 40.246503 d period are due to an occultation between the third star and the binary, then the shape of the eclipses should change over time, and the number of eclipses in one period should not always be one, but should be several times more often, like in the case of KIC 7668648 and KIC 8938628 which will be described subsequently. Since the long eclipses with a period of 40.246503 d do not change with the phase of the short period binary, it is thought that the eclipses with a 40.246503 d period indicate another binary system. Moreover, the great depth, 0.15–0.18 in normalized flux, of the eclipses with a 40.246503 d period indicates a stellar binary system rather than a system consisting of a star with a planet. The extra luminosity proportion of 0.652(0.003) means the outer binary is more luminous, and supposed to be more massive, than the inner binary. These phase light curves of 40.246503 d are not analyzed

because the lack of a secondary minimum will make the results unreliable.

Is the 40.246503 d period binary gravitationally bound to the 2.2799960 d binary, or just a blended source? Considering that a small eccentricity of 0.0035(0.0022) is needed to fit the light curve of the inner binary, and the 2.2799960 d binary is too small to generate an eccentric orbit itself³, this small eccentricity should be caused by perturbation of an outer companion. So, the binary with a 40.246503 d period is likely to be the outer companion, that is to say, it is further suggested that KIC 7622486 consists of two binaries gravitationally bound to each other, rather than two blended binaries in the sky.

3.2 KIC 7668648

Prša et al. (2011) and Slawson et al. (2011) made the first discovery and analysis this object, named KIC 7668648. Rappaport et al. (2013) and Borkovits et al. (2015) measured and analyzed its eclipse timing variations which show a 27.818590 d period, and also found some extra shallow eclipses, not due to the binary, matching the 204.8 d period $O - C$ curve. These can be used to conclude that KIC 7668648 is a triply eclipsing system. This object also has other interesting features: the object has the lowest period ratio ($P_2/P_1 < 7.3$) found so far; the mutual inclination of the binary orbital plane with respect to the orbital plane of the triple is 40.9° , which is slightly larger than the critical Kozai-Lidov oscillation inclination of 39.2° ; and the eclipses associated with the 27.818590 d period deepen continuously and rapidly.

In this paper, three sets of extraneous eclipses in addition to the binary eclipses with a period of 27.818590 d are presented. Two of the extraneous eclipses, exhibiting time intervals of 203 ± 5 d, coincide with the 204.8 d period from Borkovits et al. (2015), see Figures 2 and 3.⁴

³ If the 2.2799960 d binary is very young in age, it is possible that there is residual eccentricity from the initial formation, since its age is not long enough to achieve orbit circularization. Since KIC 7622486 is a field star and does not belong to a young star cluster, it is suggested that its age is old enough to circularize its own orbit.

⁴ The data on the figure were downloaded from 2014 August 1, instead of the updated version of 2015 April 22 or 2015 October 27, because in the new data, the eclipse disappears at 748 d, and the eclipse at 542 d is weakened. However, according to the outer period found by Borkovits et al. (2015) and the positions of other extraneous eclipses, the eclipse at 748 d is reasonable. So, it is thought that the newer data are flawed in terms of this point. Indeed a lot of noises have been smoothed out, but the real signals are also weakened or even eliminated.

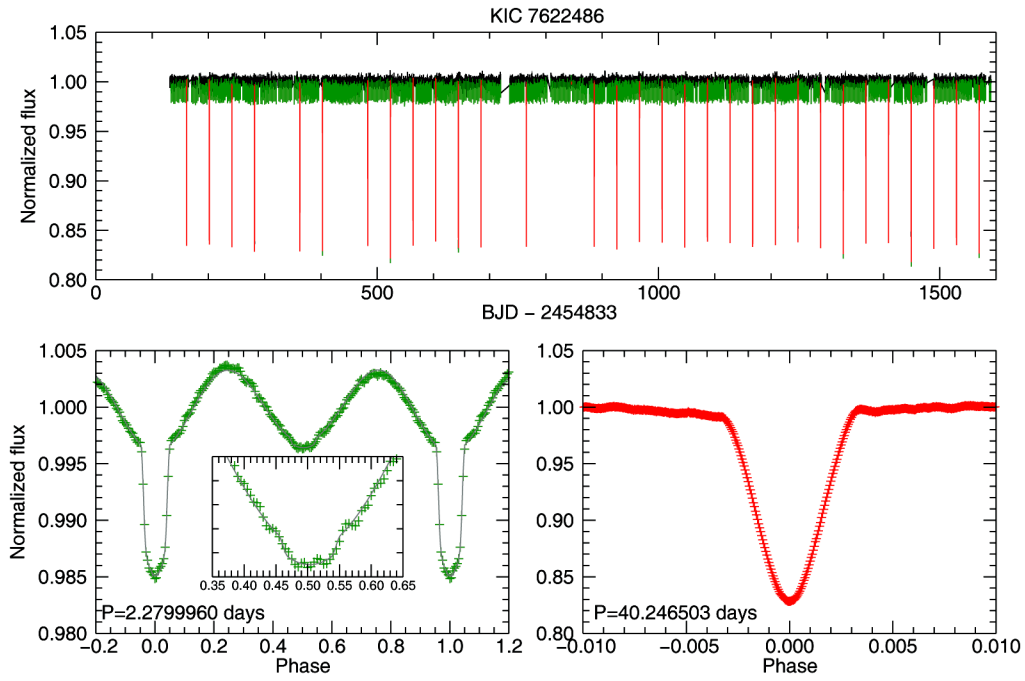


Fig. 1 The light curves of KIC 7622486. *Upper*: The whole light curves. The *green* and *red* lines are eclipses with a 2.2799960 d period and a 40.246503 d period respectively. *Lower left*: The folded phase curve of a 2.2799960 d period with a *gray* fitting line. The part around phase 0.5 is magnified and shown in the inset panel. *Lower right*: The minimum part of the folded phase curve that has a 40.246503 d period.

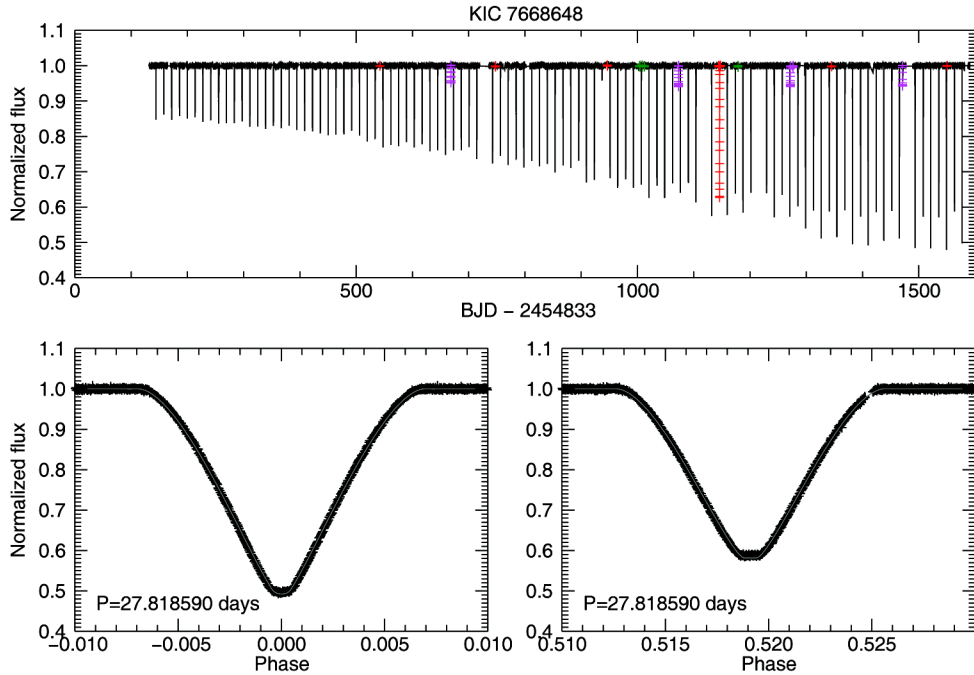


Fig. 2 The light curves of KIC 7668648. *Upper panel*: the whole light curve with a long cadence showing extraneous eclipses in *red*, *magenta* and *green* pluses. Points drawn in each color stand for different sets. The *red* and *magenta* points have the same time intervals of 204.8 d. The deepest extra eclipse around 1146 d overlaps a binary eclipse which can be seen clearly in the third left panel from the top of Fig. 3. *Lower panels*: The curves showing the 27.818590 d period binary phase at primary and secondary eclipses, which are calculated from the *Kepler* short cadence data from 1559 to 1591 d. The *gray* lines are the fittings.

Table 1 The Binary Light Curve Solutions

Parameter	KIC 7622486	KIC 7668648	KIC 7668648	KIC 7670485	KIC 8938628
Mode	detached binary	detached binary	detached binary	detached binary	detached binary
Orbital eccentricity e	0.0035(0.0022)	0.0449(0.0002)	0.0449(0.0002)	0.0241(0.0007)	0.012(0.005)
Argument of periastron ω [radian]	5.2(0.4)	5.445(0.004)	5.444(0.004)	1.98(0.01)	4.5(0.1)
Orbital inclination i [$^\circ$]	85.68(0.07)	89.993(0.004)	89.992(0.004)	89.82(0.01)	87.21(0.04)
Mass ratio m_2/m_1	0.269(0.005)	0.510(0.004)	0.979(0.005)	0.84?	0.91 ^a
Primary temperature T_1^a	7548	6449	6449	5814	6412
Temperature ratio T_2/T_1	0.49(0.02)	0.9659(0.0003)	0.9667(0.0003)	0.9747(0.0005)	0.881(0.004)
Luminosity ratio $L_1/(L_1 + L_2)$ in band <i>Kepler</i>	0.999304(0.000008)	0.5819(0.0002)	0.5822(0.0002)	0.515(0.001)	0.813(0.004)
Luminosity ratio $L_2/(L_1 + L_2)$ in band <i>Kepler</i>	0.000696(0.000008)	0.4182(0.0002)	0.4178(0.0002)	0.485(0.001)	0.187(0.004)
Luminosity ratio $L_3/(L_1 + L_2 + L_3)$ in band <i>Kepler</i>	0.652(0.003)			0.8275(0.0004)	0.33(0.01)
Modified dimensionless surface potential of star 1 Ω_1 :	4.04(0.02)	46.21(0.05)	46.68(0.05)	28.7(0.1)	21.2(0.2)
Modified dimensionless surface potential of star 2 Ω_2 :	7.4(0.1)	27.0(0.2)	50.3(0.3)	24.0(0.3)	30.7(0.4)
Radius of star 1 (relative to semimajor axis) in pole direction	0.264(0.001)	0.02189(0.00003)	0.02190(0.00002)	0.0360(0.0001)	0.0493(0.0005)
Radius of star 2 (relative to semimajor axis) in pole direction	0.044(0.001)	0.0199(0.0002)	0.0199(0.0001)	0.0368(0.0005)	0.0307(0.0004)
Radius of star 1 (relative to semimajor axis) in point direction	0.270(0.001)	0.02189(0.00003)	0.02190(0.00002)	0.0360(0.0001)	0.0493(0.0005)
Radius of star 2 (relative to semimajor axis) in point direction	0.044(0.001)	0.0199(0.0002)	0.0199(0.0001)	0.0368(0.0005)	0.0307(0.0004)
Radius of star 1 (relative to semimajor axis) in side direction	0.268(0.001)	0.02189(0.00003)	0.02190(0.00002)	0.0360(0.0001)	0.0493(0.0005)
Radius of star 2 (relative to semimajor axis) in side direction	0.044(0.001)	0.0199(0.0002)	0.0199(0.0001)	0.0368(0.0005)	0.0307(0.0004)
Radius of star 1 (relative to semimajor axis) in back direction	0.269(0.001)	0.02189(0.00003)	0.02190(0.00002)	0.0360(0.0001)	0.0493(0.0005)
Radius of star 2 (relative to semimajor axis) in back direction	0.044(0.001)	0.0199(0.0002)	0.0199(0.0001)	0.0368(0.0005)	0.0307(0.0004)

Notes: ^a Comes from Armstrong et al. (2014), indicates large uncertainty.

The left panels of Figure 3 are considered to be the binary eclipses of the tertiary star, i.e. the binary blocks the light of the tertiary star, because in the third panel from the top the binary eclipse is superposed on the long extra eclipse. Thus the right panels are considered to be the tertiary star eclipsing the binary, i.e. the tertiary star blocks the light from the binary. The eclipse depths in the right panels are significantly greater than those of the left panels, a difference of about 30 times in terms of depth of normalized flux, which indicate that the tertiary star is much fainter than the components of the binary, or the light contribution from the third body to the whole system is tiny.

The third new set of extraneous eclipses is displayed in Figure 4, where the time interval of the two panels is

about 170 d. The lower panel has more than one eclipse near a binary eclipse, indicating that a fourth body revolving around the 27.818590 d period binary may exist. In fact, many suspect extraneous eclipses are found but not shown here due to the large dispersions in the light curves. It is supposed that there may be more additional bodies which are low mass stars, and possibly including planets.

The inner binary with a 27.818590 d period was analyzed with the binary model that is part of the Wilson-Devinney program (Wilson & Devinney 1971; Wilson 1979, 1990; Van Hamme & Wilson 2007; Wilson 2008; Wilson et al. 2010; Wilson 2012), based on the short cadence data fortunately covering a full orbital period. The fitting results are shown in the lower panels of

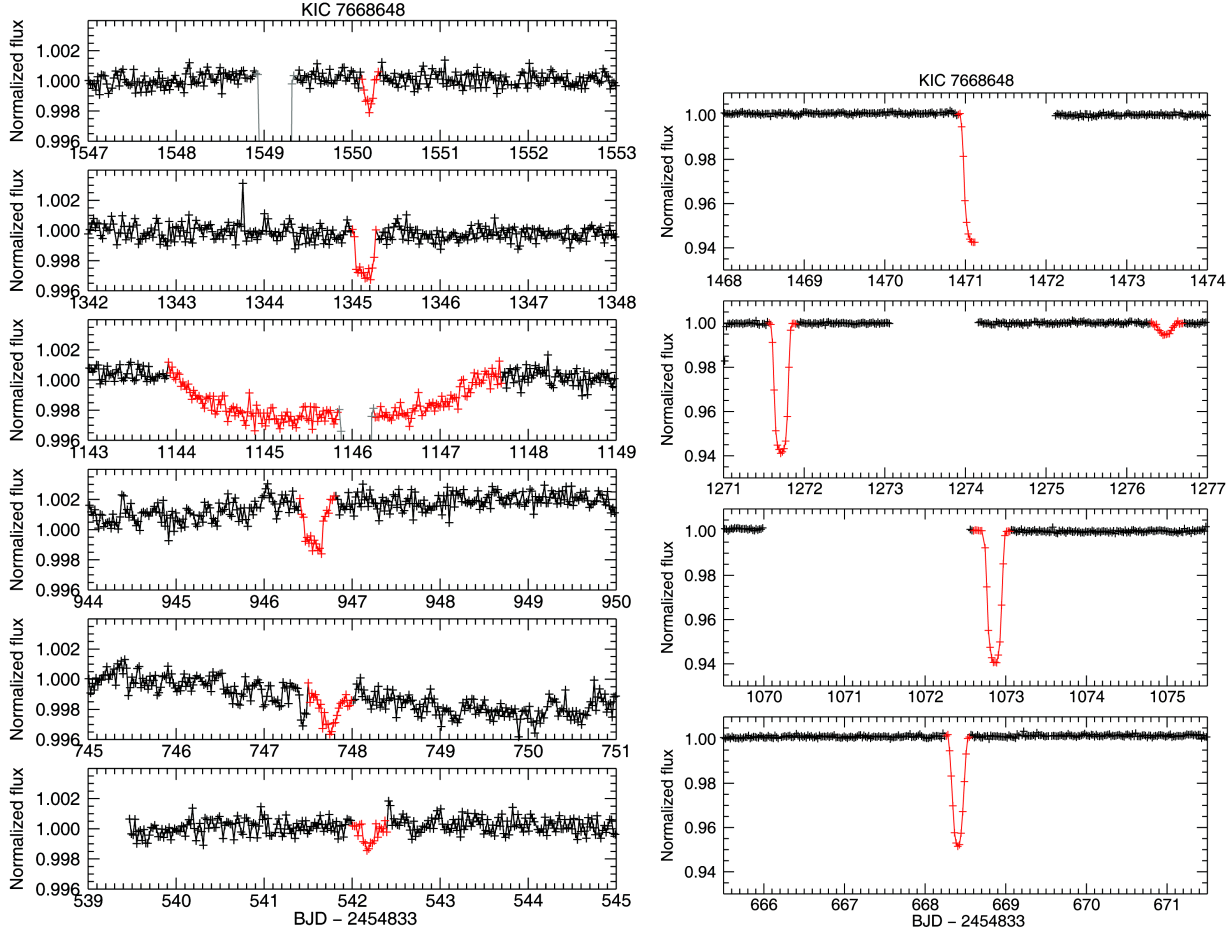


Fig. 3 The extraneous eclipses of KIC 7668648. The *red points* are the extraneous eclipses. *Left panels*: One set of light curves showing the extraneous eclipses. All these extraneous eclipses have adjacent intervals of about 203 ± 5 d. The *gray points*, only in the first and third panels from top, indicate the binary eclipses with a period of 27.818590 d which are too deep and can only be partly shown. *Right panels*: Another set of light curves showing extraneous eclipses; the adjacent intervals are also (or multiples of) 203 ± 5 d.

Figure 2 and listed in Table 1. Two solutions are listed in Table 1, which are only different in terms of mass ratio and potential of star 2. The solution with mass ratio of $0.979(\pm 0.005)$ is suggested, because it is consistent with other parameters, i.e. the temperature ratio, the luminosity ratio and the radius ratio, which are all close to 1 between the two components. The two fitting curves corresponding to the two solutions almost overlap so they cannot be distinguished in Figure 2.

The object KIC 7668648 is a highly compact triple system, whose period ratio of outer companion to inner binary $P_{\text{outer companion}}/P_{\text{inner binary}} < 7.3$ is the lowest ratio so far. Thus the inner binary of KIC 7668648 is thought to have been affected by its outer companion, which then leads to deviations from a Keplerian orbit. This will raise doubt about the applicability of the binary

model used for KIC 7668648. The differences in parameters between Table 1 and those from Borkovits et al. (2015) are partly due to these deviations. Thus the parameters from Borkovits et al. (2015) are more reliable if considering this point, since they are only based on dynamical motions, without regard to the distorted light curves.

However, there are two parameters indicating that the gravitational attraction should be very limited: first, the very small but definite eccentricity $e = 0.0449(0.0002)$ in the long orbit with a period of 27.818590 d (this can be seen more intuitively from the lower right panel of Figure 2 in which the phase of secondary minimum is clearly different from 0.5). Second, the mass of its outer companion only accounts for a small proportion, 0.144(60), and small changes in period of

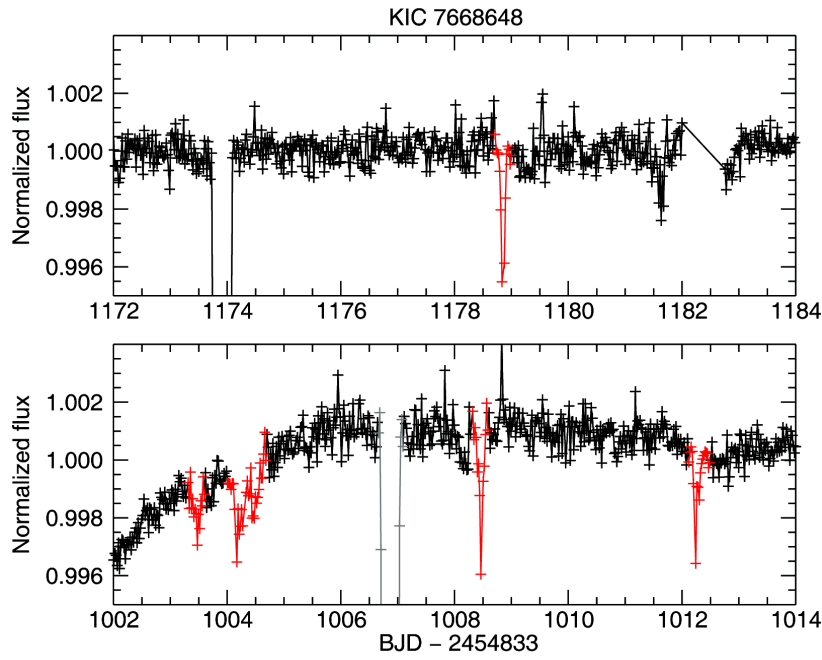


Fig. 4 The extraneous eclipses of KIC 7668648. The symbols are the same as in Fig. 3.

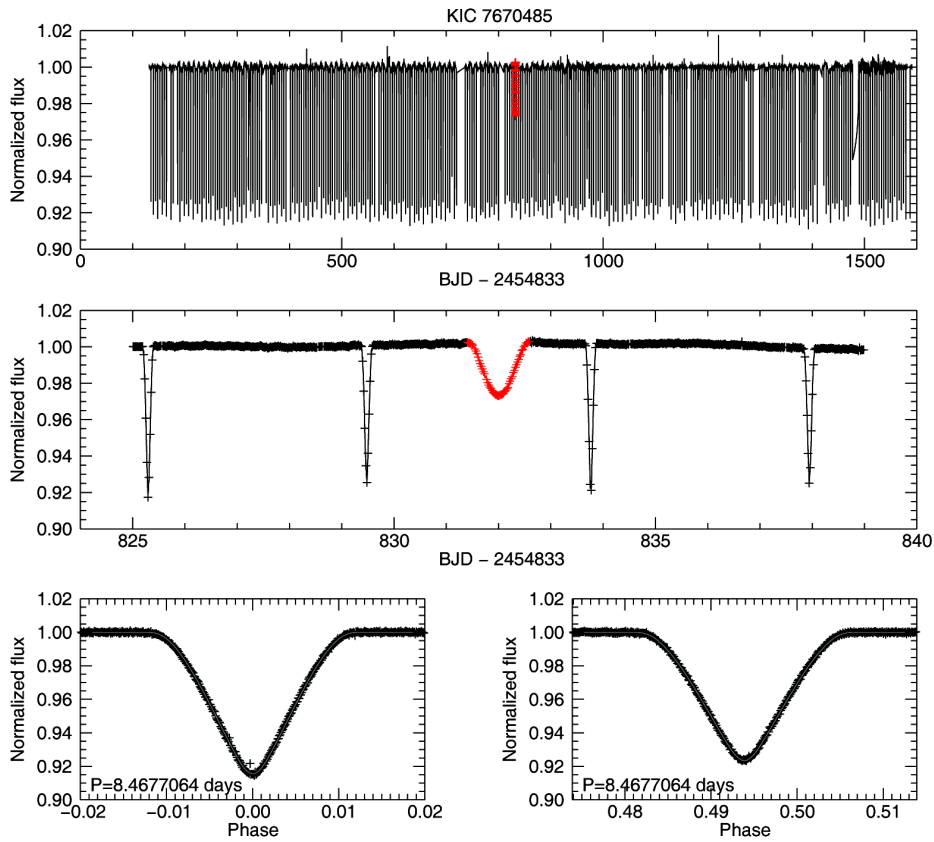


Fig. 5 *Upper*: The whole light curves of KIC 7670485 with one extra eclipse shown with *red pluses*. *Lower*: The expanded region around the extra eclipse.

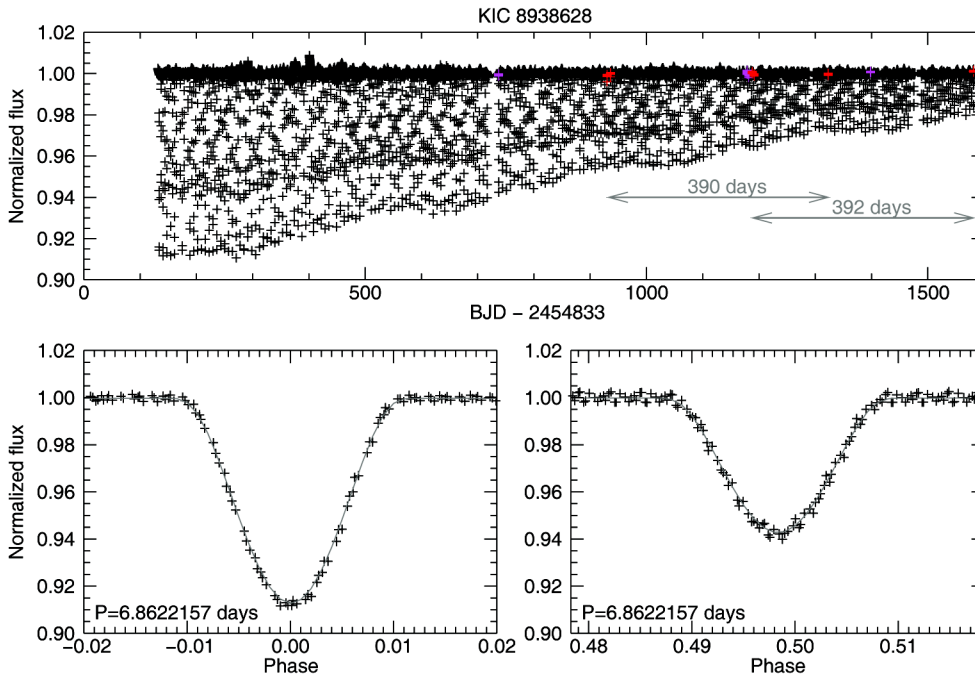


Fig. 6 *Upper*: The whole light curve of KIC 8938628. The *red* and *magenta* points are the extraneous eclipses, and the *gray* arrows are used to indicate the time intervals of the *red* points. *Lower*: The phase curves of the inner binary with a period of 6.8622157 d, shown with *gray* fitting lines.

the inner binary (Borkovits et al. 2015). Furthermore, the photometric solution presented here is self consistent. Its mass ratio, temperature ratio and radius ratio are all close to 1. In addition, the analysis program cannot converge with a positive third light value, namely the third light tends to converge to a negative value, and this situation should be caused by the extremely small proportion of the third light, which is consistent with the extraneous eclipse analysis above. Therefore finally, the solutions of KIC 7668648 by the binary model are deemed to be correct in general.

3.3 KIC 7670485

Not many papers have been published on the object KIC 7670485. Apart from the Kepler Eclipsing Binary Stars catalog of Prša et al. (2011), Slawson et al. (2011), Conroy et al. (2015) and Kirk et al. (2016), Tenenbaum et al. (2012) detected its transit signals in the first three quarters of *Kepler* data, and Armstrong et al. (2014) provided its temperatures from three photometric surveys. Here a clear and credible extra eclipse is found at 832 d, see Figure 5. The significant and symmetrical shape of the eclipse strongly suggests the existence of an additional stellar body. However, only one signal is not enough to obtain the physical parameter behind it.

The additional stellar body could be a third one around the inner binary, or another binary system, gravitationally bound or blended with the existing binary. No visible eclipse timing variations have been found so far, and the actual dispersion of its $O - C$ curve measured by us is less than 0.001 d. This shows that if the eclipse at 832 d is due to a revolving third stellar, its orbital period should be much greater than 1500 d.

The inner binary with a period of 8.4677064 d was analyzed, and the results are shown in the lower panels of Figure 5 and listed in Table 1. The mass ratio in the solution has large uncertainty, because a large range of mass ratios can give roughly the same fitting. Taking into account that the other parameter ratios are also around 1, the solution with a mass ratio around 1 is given here. The proportion of third light dominates the whole luminosity, which indicates that an extra body (or bodies) should exist, and it is much brighter than the inner binary. Based on the large proportion of third light, a binary system with greater mass is suggested to be the extra bodies.

3.4 KIC 8938628

KIC 8938628 was found to be an eclipsing binary system by Prša et al. (2011) and Slawson et al. (2011). Rappaport et al. (2013) and Borkovits et al. (2015) analyzed its

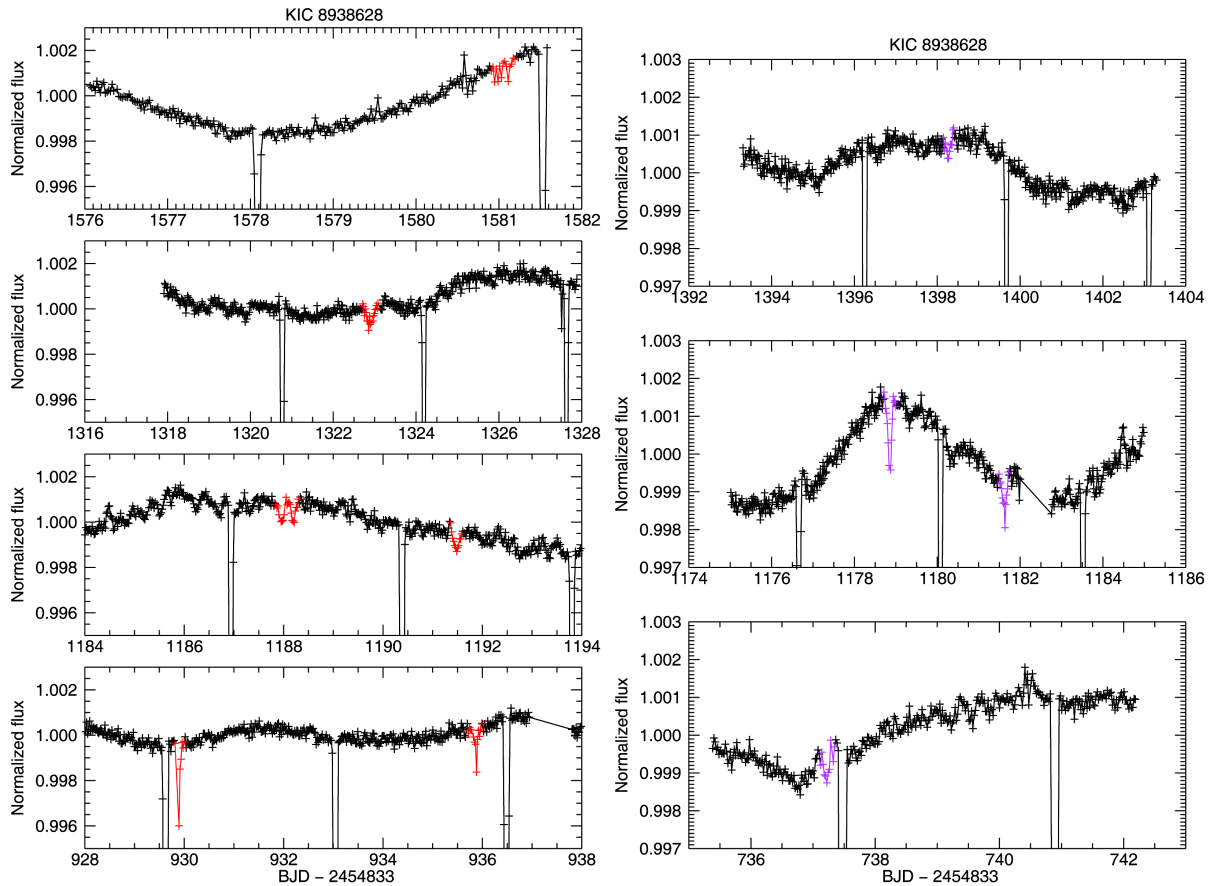


Fig. 7 The extraneous eclipses of KIC 8938628. *Left panels*: the red points are the extraneous eclipses. The time interval between extraneous eclipses in the first and third panels from the top is about 390 d, which is close to that between the second and fourth panels, about 392 d. *Right panels*: the other set of extraneous eclipses in magenta. The time intervals between them are about, or multiples of, 220 d.

monoperiodic large amplitude $O - C$ curve and concluded that a $1.12 \pm 0.28 M_{\odot}$ third star, revolving around the nearly circular orbital inner binary, has a period of 388.5 ± 0.3 d. The obvious variation of the eclipse depth can be seen from the upper panel of Figure 6, which indicates the varying inclination of the inner binary due to a noncoplanar third body nearby (Borkovits et al. 2015). If the decreasing tendency continues, the binary eclipses will disappear at about $BJD \sim 2456813$, or 2014 June 4, like the case of KIC 10319590 where eclipse depths completely disappear in ~ 400 d (Rappaport et al. 2013).

Many small dips of suspected tertiary eclipses are found on its light curves, and the most notable ones are shown in Figure 7.⁵ The extraneous eclipses are only

⁵ The data for this object, KIC 8938628, are the version from 2014 August 1. The differences between the different versions are found in cases like KIC 7668648. At around 1179 d, an evident extra eclipse was found in the version from 2014 August 1, but disappeared in the version from 2015 April 22 or later.

suspected but not substantial due to their low signal to noise ratio. However, the period information carried by the extraneous eclipses is worthy of attention. The extraneous eclipses in red, see the upper panel of Figure 6, imply an eccentric orbit with a period of about 390 d, which is very close to the 388.5 ± 0.3 d period of the third body derived by the periodic analysis method (Borkovits et al. 2015). Furthermore, the extraneous eclipses in magenta also exhibit a pattern pointing to a period of ~ 220 d. It is suggested that the object KIC 8938628 is a potential multiple eclipsing system worthy of follow-up observations.

The solution to photometric analysis of the inner 6.8622157 d period binary is displayed in Figure 6 and Table 1. The extra luminosity only accounts for a proportion of 1/3, which indicates that the extra bodies may consist of several small components so their total luminosity is low, and this is also consistent with the tiny ex-

traneous eclipses presented above. It is suggested that object KIC 8938628 is a hierarchical quadruple system.

4 SUMMARY AND DISCUSSION

In this paper four *Kepler* binaries with 57 extraneous eclipses are presented, indicating there are additional bodies around these binaries. All the binary light curves of the objects are analyzed using the binary model of the Wilson-Devinney program with good fittings. Three of the four multiple system candidates are (at least) quadruple systems, and one of them is a triple system.

KIC 7622486 is a double binary system with two striking sets of eclipses with a period of 2.2799960 d and another period of 40.246503 d. The two binary systems are thought to be gravitationally bound to each other based on the existence of a small eccentricity of 0.0035(0.0022) associated with an orbit having a period of 2.2799960 d. This system provides a very good window to study the formation of multiple systems as well as binary systems. If the two binaries share the same age, they should have formed from the same collapsing cloud. Otherwise if the two binaries have different ages, KIC 7622486 gives strong support to the theory of gravitational capture that experiences an unstable three body stage and one of the components will be ejected from the remaining stable binary system.

KIC 7668648 and KIC 8938628 are hierarchical quadruple candidates with more than one set of extraneous eclipses. Their triplicities are found by Rappaport et al. (2013) and Borkovits et al. (2015) using the $O - C$ method. The first two sets of extraneous eclipses on KIC 7668648 and the first set of extraneous eclipses on KIC 8938628 firmly confirm their triplicity with independent evidence. Moreover, the last set of extraneous eclipses on KIC 7668648 and KIC 8938628 indicates an additional body (or bodies) within the multiple systems, which make the two objects more interesting and more challenging.

For KIC 8938628, the last set of extraneous eclipses, shown in the right panels of Figure 7, may contain a period of about 220 d. If this is true, because the 220 d period of the fourth body does not differ greatly from the 388.5 ± 0.3 d period of the third body, the system cannot be stable unless the mass of the fourth body is marginal compared to other components. The fourth body may be a planet within a triple stellar system. If the 220 d period is not true, it needs more than one additional body to generate the last set of extraneous eclipses, which makes this object a quinary candidate. It should be noted that

the 220 d period cannot be from a binary system, because there are two eclipses in one group (see the middle one of the right panels in Fig. 7) which can only be from a triple eclipse structure.

Only one but a very credible extraneous eclipse was found on KIC 7670485's binary light curves, and this makes it a triple system candidate. No further meaningful information can be obtained from only one extraneous eclipse.

The high proportion of systems carrying more than one additional companion (i.e. a quadruple or higher order system, here in our four objects the proportion is 3/4) is a hint to us that multiple systems may have the tendency to form with more than three components, and also reminds us that triple systems have been found recently that are likely to have more companions. This is similar to the case of exoplanet candidates found in *Kepler* data in which approximately 40% of the candidates belong to multi-planet systems (Rowe et al. 2014).

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