LIGHT CURVE SOLUTIONS OF 12 ECCENTRIC KEPLER BINARIES AND ANALYSIS OF THEIR OUT-OF-ECLIPSE VARIABILITY

DIANA KJURKCHIEVA 1, DOROTEYA VASILEVA 1, AND DINKO DIMITROV 2
1 Department of Physics, Shumen University, 9700 Shumen, Bulgaria
2 Institute of Astronomy and NAO, Bulgarian Academy of Sciences, Tsarigradsko shossee 72, 1784 Sofia, Bulgaria

Received 2016 June 12; revised 2016 September 7; accepted 2016 September 7; published 2016 November 23

ABSTRACT

The eccentricity, periastron angle, orbital inclination, mass ratio, stellar temperatures, and relative stellar radii of 12 eclipsing eccentric binaries were determined on the basis of Kepler data. The analysis of their out-of-eclipse variability led to the following results: (i) KIC 10490980 exhibits rotational (spot-type) variability. (ii) Four new heartbeat stars were found: KIC 9344623 and KIC 10296163, which have wide tidally induced light humps, and KIC 9119405 and KIC 9673173, which have narrow “W-shape” features. (iii) KIC 4932691 shows oscillations with approximately the 18th harmonic of the orbital period. We established that the eccentric Kepler binaries fall below the envelope $P(1 - e^2)^{3/2} \approx 5$ days on the period–eccentricity diagram and that there is a surprising lack of eccentric binaries with periods of 25–35 days.

Key words: binaries: eclipsing – stars: fundamental parameters

1. INTRODUCTION

Until half a century ago eccentric binary systems were objects mainly of celestial mechanics. Recently, they have become important targets of modern astrophysics because their investigation provides observational tests for the theory of tidal forces and for models of stellar structure and evolution (Fuller & Lai 2011). Eccentric binary systems have been used as probes for studying the mechanisms for circularization of the orbits, the synchronization of stellar rotation with the orbital motion and coplanarity, the impermanent mass transfer occurring close to the periastron, and apsidal motion (Kopal 1978; Sepinsky et al. 2007; Claret & Gimenez 2010; Lajoie & Sills 2011). Despite the recent great progress in the study of eccentric binary stars, there remain debatable problems: the dependence of period and eccentricity and its evolutionary meaning, the empirical relations between the stellar parameters of eccentric binaries; the existence of highly eccentric binaries with short periods, etc.

An important step in the field was made by Kepler. This mission’s high-accuracy observations have made it possible to detect tidally induced brightening and oscillations, which were theoretically predicted by Kumar et al. (1995). The newly discovered “heartbeat” stars represent unique laboratories for investigation of these higher-order effects (Welsh et al. 2011; Burkart et al. 2012; Thompson et al. 2012; Fuller & Lai 2012). Moreover, tidally induced pulsations could explain the driving mechanism of excitation of certain oscillation modes (Willems & Aerts 2002). The study of Doppler boosting has also become possible (Bolomo et al. 2011).

According to the analytic model of Kumar et al. (1995), the shape of the light increase around the periastron is one-peaked for $i < 30^\circ$ but becomes two-peaked with a central dip (whose depth and width increase with $i$) for a bigger orbital inclination. The shapes of the tidally induced features of 16 eccentric (non-eclipsing) Kepler binaries discovered by Thompson et al. (2012) were different: with a dip before brightening, with a dip after brightening, and with a distinct “W” or “M” shape. We also found tidally induced brightening for several eclipsing eccentric Kepler binaries (Kjurkchieva & Vasileva 2015a, 2016; Kjurkchieva et al. 2016), but with a “Λ” (hump) shape instead of a two-peaked profile. More statistics are necessary for investigation of this newly discovered phenomenon.

This paper presents the results of our study of a sample of 12 Kepler binaries with narrow eclipses (widths in the range 0.006–0.036 in phase units) but still allowing acceptable light curve solutions. The aims of our investigation were (i) to obtain their orbits and physical parameters and thus to provide new data for establishment/ improvement of the empirical relations between the parameters of eccentric binaries and (ii) to analyze their out-of-eclipse variability and to search for tidally induced effects.

2. LIGHT CURVE SOLUTIONS

Table 1 presents information for our targets from the EB catalog (Prsa et al. 2011; Slawson et al. 2011): orbital period $P$, Kepler magnitude $m_K$; mean temperature $T_m$; widths of the primary and secondary eclipses $w_{1,2}$ (in phase units); and depths of the eclipses $d_{1,2}$ (in flux units). These parameters have been obtained by an automated (pipeline) reduction of the Kepler data and/or preliminary ground-based photometric observations.

Long cadence (LC) data from almost all quarters are available in the Kepler archive for the whole sample. They reveal that besides eclipses the targets exhibit additional out-of-eclipse variability (see Section 3). To ignore this effect in the procedure of the light curve solutions, we modeled all available photometric data after appropriate phase binning.

We used the package PHOEBE (Prsa & Zwitter 2005) for modeling. The procedure is described in detail in Kjurkchieva and Vasileva (2015a). Briefly, it consists of several steps: preliminary calculation of the eccentricity $e$ and periastron angle $\omega$; varying of $e$ and $\omega$ to fit the eclipse phases; varying of the inclination $i$, mass ratio $q$, secondary temperature $T_2$, and potentials $\Omega_{1,2}$ (relative stellar radii $r_{1,2}$) to reproduce the whole curve; and adjusting the component temperatures around the mean target temperature $T_m$.

Table 2 shows the values of the orbital and stellar parameters corresponding to our light curve solutions (the periastron phase $\varphi_{\text{per}}$ and the ratio of relative luminosities $L_2/L_1$ were not free but calculated parameters). The numbers in brackets in Table 2...
Table 1
Parameters from the EB Catalog: Orbital Period $P$; Kepler Magnitude $m_K$; Mean Temperature $T_m$; Widths of the Primary and Secondary Eclipses $w_1$, $w_2$ (in Phase Units); Depths of the Eclipses $d_1$, $d_2$ (in Flux Units)

| Star         | $P$ (days) | $m_K$  | $T_m$  | $w_1$  | $w_2$  | $d_1$  | $d_2$  |
|--------------|------------|--------|--------|--------|--------|--------|--------|
| KIC 4932691 | 18.1120792 | 13.627 | 7109   | 0.0134 | 0.0107 | 0.1114 | 0.0376 |
| KIC 6841577 | 15.5375346 | 14.875 | 5478   | 0.0134 | 0.0174 | 0.2098 | 0.0171 |
| KIC 8610483 | 48.7993681 | 15.05  | 5920   | 0.0072 | 0.0118 | 0.2783 | 0.1224 |
| KIC 8378922 | 43.2630585 | 14.977 | 5438   | 0.0078 | 0.0157 | 0.3381 | 0.2187 |
| KIC 9025914 | 11.3203214 | 16.756 | 5900   | 0.0146 | 0.02   | 0.2344 | 0.0338 |
| KIC 9344623 | 14.7594793 | 13.822 | 6312   | 0.0223 | 0.019  | 0.3367 | 0.3107 |
| KIC 10296163| 9.2967444  | 13.211 | 6229   | 0.0262 | 0.0158 | 0.2057 | 0.0256 |
| KIC 5986209 | 23.7377097 | 15.147 | 5345   | 0.0055 | 0.0126 | 0.3368 | 0.0868 |
| KIC 12217907| 43.2045856 | 14.291 | 5745   | 0.0125 | 0.0066 | 0.2047 | 0.0613 |
| KIC 9119405 | 18.6463233 | 13.729 | 5569   | 0.0163 | 0.0208 | 0.2195 | 0.1881 |
| KIC 10490960| 5.6824111  | 14.3   | 5787   | 0.0327 | 0.0365 | 0.2038 | 0.1973 |
| KIC 9673173 | 21.29474    | 13.731 | 5838   | 0.0136 | 0.0128 | 0.111  | 0.0939 |

Table 2
Parameters of the Best Light Curve Solutions: Eccentricity $e$; Periastron Angle $\omega$; Periastron Phase $\varphi_{\text{per}}$ (Counted from the Primary Minimum); Inclination $i$; Mass ratio $q$; Stellar Temperatures $T_1$, $T_2$; Relative Stellar Radii $r_1$, $r_2$; Ratio of Relative Stellar Luminosities $I_2/I_1$

| Star         | $e$       | $\omega$ (deg) | $\varphi_{\text{per}}$ | $i$   | $q$   | $T_1$ (K) | $T_2$ (K) | $r_1$  | $r_2$  | $I_2/I_1$ |
|--------------|-----------|----------------|--------------------------|-------|-------|-----------|-----------|--------|--------|-----------|
| KIC 4932691  | 0.37886(1)| 181.7(7)       | 0.14                     | 88.06(2)| 0.393(3)| 7164(48)  | 5473(28)  | 0.0436 | 0.0153 | 0.050    |
| KIC 6841577  | 0.12280(3)| 162.3(4)       | 0.16                     | 88.81(3)| 0.316(2)| 5569(19)  | 3601(12)  | 0.0391 | 0.0176 | 0.046    |
| KIC 8610483  | 0.3936(1) | 32.9(4)        | 0.93                     | 88.81(4)| 0.468(4)| 6158(14)  | 5653(3)   | 0.0174 | 0.0205 | 0.963    |
| KIC 8378922  | 0.2935(1) | 112.8(2)       | 0.03                     | 89.09(1)| 0.573(5)| 5548(20)  | 5356(25)  | 0.0229 | 0.0234 | 0.902    |
| KIC 9025914  | 0.38029(8)| 55.4(4)        | 0.87                     | 88.07(6)| 0.607(5)| 6165(19)  | 4327(15)  | 0.0446 | 0.0219 | 0.052    |
| KIC 9344623  | 0.18902(5)| 191.5(2)       | 0.31                     | 88.99(2)| 0.658(5)| 6395(12)  | 6241(12)  | 0.0470 | 0.0374 | 0.579    |
| KIC 10296163 | 0.3674(1) | 228.2(2)       | 0.29                     | 88.53(2)| 0.401(3)| 6292(14)  | 4121(18)  | 0.0570 | 0.0258 | 0.030    |
| KIC 5986209  | 0.3482(2) | 55.5(2)        | 0.96                     | 89.10(3)| 0.339(8)| 5503(25)  | 4868(24)  | 0.0188 | 0.0144 | 0.333    |
| KIC 12217907 | 0.38819(4)| 228.7(1)       | 0.28                     | 89.54(3)| 0.482(6)| 5859(15)  | 4736(13)  | 0.0253 | 0.0114 | 0.078    |
| KIC 9119405  | 0.44113(1)| 168.3(5)       | 0.09                     | 88.08(4)| 0.980(1)| 5549(22)  | 5573(24)  | 0.0525 | 0.0275 | 0.280    |
| KIC 10490960 | 0.10173(7)| 41.0(7)        | 0.88                     | 86.32(9)| 0.949(6)| 5763(34)  | 5838(31)  | 0.0898 | 0.0586 | 0.449    |
| KIC 9673173  | 0.56510(1)| 0.8(4)         | 0.92                     | 87.22(4)| 0.752(1)| 5856(12)  | 5683(14)  | 0.0436 | 0.0158 | 0.102    |

3. OUT-OF-ECLIPSE VARIABILITY

All targets exhibit cyclic out-of-eclipse light variability with the orbital period (excluding KIC 4932691) of different types.

3.1. Rotational Variability

The out-of-eclipse light curve of KIC 10490980 exhibits long-term modulation with amplitudes up to 0.01 mag and timescale of a hundred days (Figure 2). The tracing of light variability through several consecutive cycles reveals rotational (spot-type) variability (Figure 2). Then the long-term modulation may be explained by the spot activity cycle of KIC 10490980.

3.2. New Heartbeat Stars

We found tidally induced light brightening with amplitude 0.0004–0.0010 mag around the periastron phase of KIC 10296163, KIC 9344623, KIC 9673173, and KIC 9119405 (Figure 3).

The features observed around the periastron of KIC 9344623 and KIC 10296163 as well as the corresponding synthetic PHOEBE features are wide and have simple “λ” (hump) shapes (Figure 3, top row).

The most interesting features at the periastron phases belong to KIC 9119405 and KIC 9673173, the targets with the
greatest eccentricities from our sample. These features are relatively narrow and have complex “W-shape” profiles (Figure 3, bottom row). The synthetic PHOEBE features reproduce the observed ones well (although not perfectly).

We found that the non-eclipsing star KIC 10873904 from the sample of Thompson et al. (2012) exhibits similar “W-shape” tidally induced brightening with amplitude of 0.001 mag (modeled by orbital parameters $e = 0.436$, $\omega = 347^\circ$, and $i = 42^\circ$).

Figure 1. Top of each panel: the light curve of the target around the eclipses and its PHOEBE fit; bottom: the corresponding residuals.
The observed out-of-eclipse light curve of KIC 4932691 (Figure 4), the target with the highest temperature, exhibits oscillations with amplitudes of 0.002–0.004 mag and a period of 1.01626 day (almost 18 times shorter than the orbital cycle). These light variations have a simple one-waved shape (Figure 5) and could be considered as oscillations at the 18th harmonic of the orbital period, i.e., they could be attributed to the second tidally induced phenomenon predicted by Kumar et al. (1995). Most of the heartbeat targets of Thompson et al. (2012) have oscillations that are harmonics of the orbital period, but almost all of them have higher temperatures than our targets. This implies that tidally induced oscillations are inherent to early MS stars.

3.4. Artificial Light Increasing at the Eclipses

KIC 8610483, KIC 8378922, KIC 5986209, KIC 12217907, KIC 6841577, and KIC 9025914 reveal strange light increasing around the eclipses (Figure 6). It is more apparent at the secondary eclipse (excluding KIC 12217907) and reaches 0.0008 mag. We established that this “volcano effect” was inherent only for the targets with the narrowest eclipses (ω1,2 ≤ 0.018). It turned out, however, that such a feature is not present in their raw data (Figure 7). Hence, we suppose that it is an artificial effect that is a result of the imperfect guiding of the telescope and the corresponding de-trending procedure of the Kepler data. This supposition explains why the synthetic PHOEBE light curves do not reproduce at all the observed light increasing around the eclipses of these targets (Figure 6).

4. LOCATION ON THE PERIOD–ECCENTRICITY DIAGRAM

One of the most interesting and debatable relations of eccentric binaries is period–eccentricity. Different attempts have been made in the past to explain the observed trend that binaries with longer periods have greater eccentricities, including studies of tidal action (Russell 1910), secular decrease in the stellar mass (Jeans 1924), and the effect of encounters (Walters 1932a, 1932b). Zahn (1977) and Lecar et al. (1976) concluded that the tidal effect is especially effective for the circularization of orbits of late stars with convective envelopes.

Horrocks (1936) has derived the theoretical dependence of period and eccentricity $P \approx e^{3/2} = \text{const}$, which has been confirmed by parameters of binaries with periods $P > 5$ days. Mayor and Mermilliod (1984) studied red dwarfs in open clusters and found that the orbits of those with periods shorter than 5.7 days are circular, while binaries with longer periods have eccentric orbits. Mathieu et al. (1990) obtained similar results for 8 evolved MS binaries belonging to old open cluster M67, but determined a cut-off period of around 11 days.

Duquennoy and Mayor (1991) revealed that binaries with $P < 10$ days have eccentricities close to zero, while those with longer periods exhibit a complex $(e, P)$ diagram. According to Raghavan et al. (2010) the period–eccentricity relation of solar-type stars shows the expected circularization for periods below 12 days (caused by tidal forces over the age of the Galaxy), followed by a roughly flat distribution for $10 < P < 1000$ days. The sample of Raghavan et al. (2010) is limited by an upper envelope $P(1 - e^2)^{3/2} = 10$ days, while the fifteen highly eccentric Kepler binaries studied by Dong et al. (2013) appear...
between the tracks of constant angular momentum corresponding to 10 and 30 days.

The places on the period–eccentricity diagram of all 32 Kepler binaries we have so far studied (Kjurkchieva & Vasileva 2015a, 2015b, 2016; Kjurkchieva et al. 2016) reveal the following trends (Figure 8): (i) There is a fast increase of eccentricity (up to 0.57) with the period for targets with periods of 4 days < \( P < 25 \) days; (ii) there is a second increase of eccentricity beginning from \( e = 0.1 \) for periods \( P \geq 35 \) days; and (iii) there are no targets with periods within 25–35 days, which may mean the existence of a short stage of evolution of binaries connected with a fast change of their orbits.

We built a common \((P, e)\) diagram for all Kepler eccentric binaries (Figure 9). The targets of Dong et al. (2013) and Beck et al. (2014) fall below the envelope \( P(1 - e^2)^{3/2} \approx 5 \) days (Figure 9). Most of the members of the catalog of Bulut and Demircan (2007) containing above a hundred eccentric binaries appeared on the left of the last envelope (Figure 9).

Analysis of the common \((e, P)\) distribution of the known eccentric binaries led us to several results:

(a) There are many short-period binaries (with periods of several days) with considerable eccentricities. Hence, a limited by the foregoing envelope. In fact, all our binaries fall below the envelope \( P(1 - e^2)^{3/2} \approx 5 \) days (Figure 9). Most of the members of the catalog of Bulut and Demircan (2007) containing above a hundred eccentric binaries appeared on the left of the last envelope (Figure 9).

Analysis of the common \((e, P)\) distribution of the known eccentric binaries led us to several results:

(a) There are many short-period binaries (with periods of several days) with considerable eccentricities. Hence, a

\[ \text{Figure 5. The out-of-eclipse brightness of KIC 4932691 folded by a period of 1.01626 days.} \]

\[ \text{Figure 4. The oscillations of KIC 4932691.} \]

\[ \text{Figure 6. Folded out-of-eclipse light curves of the targets with “volcano effect.”} \]
possible conclusion is that there is no sharp cut-off of the \((e, P)\) distribution.

(b) The distribution of eccentric binaries with periods below 260 days reveals a roughly linear trend of the increase of eccentricity with the period (Figure 9), which is expected from the theory of binary evolution.

(c) There are no targets with periods of 25–35 days among all (around 180 in number) eccentric binaries shown in Figure 9.

5. CONCLUSIONS

The main results of our study are as follows:

(1) We determined the orbital and stellar parameters of 12 eclipsing binaries with eccentric orbits from the Kepler archive. Their eccentricities are between 0.1 and 0.56, and most of them show partial eclipses (KIC 12217907 and KIC 10296163 have total eclipses). The temperatures of the stellar components correspond to a spectral type from early F to late K.

(2) We found out-of-eclipse light variability of different types: (i) KIC 10490980 reveals rotational (spot-type) variability. (ii) Four targets show tidally induced light features around the periastron phase—i.e., they are heartbeat stars. KIC 9344623 and KIC 10296163 have wide humps, while KIC 9119405 and KIC 9673173 (the targets with the greatest eccentricities) have narrow “W-shape” profiles. (iii) KIC 4932691 reveals oscillations with approximately the 18th harmonic of the orbital period.

(3) The eccentric Kepler binaries fall below the envelope \(P(1 - e^2)^{3/2} \approx 5\) days on the period–eccentricity diagram. We established a lack of eccentric binaries with periods of 25–35 days.

Our investigation may be considered as an expansion of the study of heartbeat stars of Thompson et al. (2012) to eclipsing binaries. It requires further, more in-depth analysis and interpretation in the framework of the evolutional scenarios of binary systems.

The research was supported partly by funds of project RD 08-81/03.02.2016 of Shumen University. It used the SIMBAD database and NASA Astrophysics Data System Abstract Service. We worked with the live version of the Kepler EB catalog (http://keplerarchive.villanova.edu/). The authors are grateful to the anonymous referee for the valuable recommendations and notes.

REFERENCES

Beck, P., Hambleton, K., Vos, J., et al. 2014, A&A, 564A, 36

Bloomen, S., Marsh, T. R., Østensen, R. H., et al. 2011, MNRAS, 410, 1787

Bulut, I., & Demircan, O. 2007, MNRAS, 378, 179

Burkart, J., Quataert, E., Arras, P., & Weinberg, N. N. 2012, MNRAS, 421, 983

Claret, A., & Gimenez, A. 2010, A&A, 519A, 57

Dong, S., Katz, B., & Socrates, A. 2013, ApJ, 763L, 2

Duqennoy, A., & Mayor, M. 1991, A&A, 248, 485

Fuller, J., & Lai, D. 2011, MNRAS, 412, 1331

Fuller, J., & Lai, D. 2012, MNRAS, 420, 3126

Figure 7. Out-of-eclipse light variability of KIC 8378922. Top: the automatically de-trended data with “volcano effect”; bottom: phased raw data from quarters Q5 and Q13 (shifted vertically by 0.006).

Figure 8. Period–eccentricity diagram for our 32 Kepler targets.

Figure 9. Period–eccentricity diagram of short-period eccentric binaries: pluses for the sample of Bulut and Demircan (2007); red circles for our 32 Kepler binaries; green triangles for the Kepler targets of Beck et al. (2014); blue squares for the Kepler binaries of Dong et al. (2013); and continuous green and violet lines describing tracks of constant angular momentum \(P(1 - e^2)^{3/2}\) corresponding to 10 and 5 days.
Hambleton, K., Kurtz, D. W., Prša, A., et al. 2013, MNRAS, 434, 925
Horrocks, H. 1936, MNRAS, 96, 534
Jeans, J. H. 1924, MNRAS, 85, 2
Kipping, D. 2010, MNRAS, 408, 1758
Kjurkchieva, D., & Vasileva, D. 2015a, PASA, 32, 23
Kjurkchieva, D., & Vasileva, D. 2015b, BlgAJ, 23, 75
Kjurkchieva, D., & Vasileva, D. 2016, NewA, 48, 30
Kjurkchieva, D., Vasileva, D., & Dimitrov, D. 2016, Ap&SS, 361, 132
Kopal, Z. 1978, Dynamics of Close Binary Systems, Astrophysics and Space Science Library, Vol. 68 (Dordrecht: D. Reidel)
Kumar, P., Ao, C., & Quataert, E. 1995, ApJ, 449, 294
Lajoie, C., & Sills, A. 2011, ApJ, 726, 67
Lecar, M., Wheeler, J. C., & McKee, C. F. 1976, ApJ, 205, 556
Lehmann, H., Southworth, J., Tkachenko, A., & Pavlovski, K. 2013, A&A, 557A, 79
Maceroni, C., Lehmann, H., da Silva, R., et al. 2014, A&A, 563A, 59
Mathieu, R., Latham, D., & Griffin, R. 1990, AJ, 100, 1859
Mayor, M., & Mermilliod, J. 1984, in Proc. IAU Symp. 105, Observational Tests of the Stellar Evolution Theory., Switzerland, ed. A. Maeder & A. Renzin (Dordrecht: D. Reidel), 411
Prsa, A., & Zwitter, T. 2005, ApJ, 628, 426
Prsa, A., Batalha, N., Slawson, R., et al. 2011, AJ, 141, 83
Raghavan, D., McAlister, H., Henry, T., et al. 2010, ApJS, 190, 1
Russell, H. N. 1910, ApJ, 31, 185
Sepinsky, J. F., Willems, B., & Kalogera, V. 2007, ApJ, 660, 1624
Slawson, R., Prša, A., Welsh, W., et al. 2011, AJ, 142, 160
Thompson, S. E., Everett, M., Mullally, F., et al. 2012, ApJ, 753, 86
Walters, M. H. 1932a, MNRAS, 92, 786
Walters, M. H. 1932b, MNRAS, 93, 28
Welsh, W., Orosz, J., Aerts, C., et al. 2011, ApJS, 197, 4
Willems, B., & Aerts, C. 2002, A&A, 384, 441
Zahn, J. P. 1977, A&A, 57, 383