Light curve solutions of the eclipsing eccentric binaries KIC 8111622, KIC 10518735, KIC 8196180 and their out-of-eclipse variability

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Abstract We determined the orbits and stellar parameters of three eccentric eclipsing binaries by light curve solutions of their Kepler data. KIC 8111622 and KIC 10518735 undergo total eclipses while KIC 8196180 reveals partial eclipses. The target components are G and K stars, excluding the primary of KIC 8196180 which is early F star. KIC 8196180 reveals well-visible tidally-induced feature at periastron, i.e. it is an eclipsing heartbeat star. The characteristics of the observed periastron feature (shape, width and amplitude) confirm the theoretical predictions. There are additional out-of-eclipse variations of KIC 8196180 with the orbital period which may be explained by spot activity of synchronously rotating component. Besides worse visible periastron feature KIC 811162 exhibits small-amplitude light variations whose period is around 2.3 times shorter than the orbital one. These oscillations were attributed to spot(s) on asynchronously rotating component.

Keywords binaries: eclipsing – methods: data analysis – stars: fundamental parameters – stars: individual (KIC 8111622, KIC 10518735, KIC 8196180)

1 INTRODUCTION

The eccentric binaries are important objects for the modern astrophysics because they present probes for study of tidal interaction. The gradual loss of energy due to tidal forces leads to circularization of the orbit and the synchronization of the rotation of these stars with their orbital motion (Tassoul 1988). The unprecedented high-accuracy of Kepler observations and their continuity (Borucki et al. 2010; Koch et al. 2010) allowed to discover many new eccentric binaries as well as to confirm the second-order effects predicted by Kumar, Ao and Quataert (1995): light feature at the periastron and tidally-excited oscillations (Welsh et al. 2011; Fuller and Lai 2011; Burkart et al. 2011; Thompson et al. 2012; Nicholls and Wood 2012; Hambleton et al. 2013). The newly discovered objects were called "heartbeat" (HB) stars. They provide important tests for the stellar astrophysics and information about the stellar interiors (Hambleton et al. 2013).

The number of heartbeat stars found in the Kepler data gradually increases (Kirk et al. 2016). Some of them have been objects of follow-up spectroscopy which shows a good agreement between the spectroscopic and photometric orbital elements (Smullen and Kobulnicky 2013; Shporer et al. 2016). Last years we studied around 30 eccentric Kepler binaries, 12 of them turned out heartbeat stars (Kjurkchieva and Vasileva 2015; 2016; Kjurkchieva, Vasileva and Dimitrov 2016).

The goal of this study is determination of the orbits and physical parameters of three eccentric binaries, KIC 8111622, KIC 10518735, KIC 8196180, as well as investigation of their out-of-eclipse variability to search for tidally-excited effects. Table 1 presents available information for these targets from the EB catalog (Prsa et al. 2011; Slawson et al. 2011; Kirk et al. 2016).

2 Light curve solutions

The modeling of Kepler data was carried out by the package PHOEBE (Prsa and Zwitter 2005). We used
Table 1 Parameters of the targets from the EB catalog: orbital period $P$, mean temperature $T_m$, widths $w_{1,2}$ of the eclipses (in phase units), depths of the eclipses $d_{1,2}$ (in flux units), phase of the secondary eclipse $\varphi_2$

| Kepler ID     | $P$ [d]    | $K_{cm}$ | $T_m$ [K] | $w_1$ | $w_2$ | $d_1$ | $d_2$ | $\varphi_2$ |
|--------------|------------|----------|-----------|-------|-------|-------|-------|-------------|
| 8111622      | 15.4460592 | 15.488   | 5663      | 0.0104| 0.0135| 0.318 | 0.183 |             |
| 10518735     | 19.515     | 16.739   | 5146      | 0.0084| 0.0093| 0.208 | 0.142 | 0.815       |
| 8196180      | 3.6716611  | 12.814   | 7114      | 0.0409| 0.0409| 0.128 | 0.044 | 0.404       |

its mode “Detached binaries” because their light curves (Fig. 1) imply such configurations.

Long cadence (LC) data from different quarters are available in the *Kepler* archive for these binaries. To ignore the effect of accidental light fluctuations in the procedure of the light curve solutions and to accelerate the light curve synthesis, we modelled all available LC photometric data (above 50000 points for each target) after phase binning. We used 2000 bins in phase (the value of PHOEBE leading to maximum number points, important for targets with narrow eclipses).

The procedure of the light curve solutions consists of several steps.

1. **Calculation of initial (approximate) values of some parameters**

   Preliminary values of the eccentricity $e$ and periastron angle $\omega$ were calculated according to the formulae (Kjurkchieva and Vasileva 2013):

   \[
   e_0 \cos \omega_0 = \frac{\pi}{2}[(\varphi_2 - \varphi_1) - 0.5] \tag{1}
   \]

   \[
   e_0 \sin \omega_0 = \frac{w_2 - w_1}{w_2 + w_1} \tag{2}
   \]

   where the values of $\varphi_2$, $w_1$ and $w_2$ were taken from Table 1 ($\varphi_1=0$).

   Assuming that the target components are MS stars and $T_i^1 = T_m$, we calculated initial values of secondary temperature $T_i^2$, mass ratio $q(T')$ and relative stellar radii $r_i$ by the formulas (see Appendix)

   \[
   T_i^2 = T_i^1 \left( \frac{d_2}{d_1} \right)^{1/4}, \quad q(T') = \left( \frac{T_i^2}{T_i^1} \right)^{1.6} \tag{3}
   \]

   \[
   \frac{r_i^2}{r_i^1} = [q(T')]^{0.75}, \quad r_i^1 + r_i^2 \approx \pi w \tag{4}
   \]

   where $w$ is the mean eclipse width from Table 1 while $d_{1,2}$ are the depths of eclipses.

2. **Light curve solution by PHOEBE**

   The solution of light curve for detached binary is quite insensitive to the mass ratio in opposite to semidetached and overcontact configurations (Terrell and Wilson 2005). That is why we fixed this parameter of our targets (Table 2) to its value from equation (3). To search for the best fit to the data we varied the following parameters: $e$ and $\omega$ around their preliminary values $e_0$.
Fig. 3  The same as figure 1 for KIC 8196180

Table 2  Fixed, fitted and calculated parameters of the light curve solutions: mass ratio $q(T^i)$ calculated by the initial component temperatures; eccentricity $e$; periastron angle $\omega$; inclination $i$; temperature of the secondary star $T_2$; surface potentials $\Omega_{1,2}$; relative radii of the primary and secondary stars $r_{1,2}$; periastron phase $\varphi_{per}$; luminosity ratio of the stellar components $L_2/L_1$; calculated temperatures of the primary and secondary stars $T_{1,2}^f$; calculated mass ratios $q(L)$ and $q(T^f)$ from the luminosity ratio and final component temperatures; value $q_{fit}$ obtained by arbitrary varying of the mass ratio.

| Kepler ID   | 8111622 | 10518735 | 8196180 |
|-------------|---------|----------|---------|
| $q(T^i)$    | 0.378   | 0.858    | 0.634   |
| $e$         | 0.533(2)| 0.519(2) | 0.151(1) |
| $\omega$ [deg] | 165.7(3)| 5.4(2)   | 180.5(1) |
| $i$ [deg]   | 88.90(2)| 88.42(3) | 83.40(1) |
| $T_2$ [K]   | 3620(15)| 4857(30)| 5319(8)  |
| $\Omega_1$  | 29.12(5)| 40.37(9)| 8.46(2)  |
| $\Omega_2$  | 21.13(4)| 51.05(9)| 11.53(3) |
| $r_1$       | 0.0352(2)| 0.0259(4)| 0.1290(3)|
| $r_2$       | 0.0192(1)| 0.0174(3)| 0.0622(1)|
| $\varphi_{per}$ | 0.070   | 0.917    | 0.201    |
| $L_2/L_1$   | 0.051   | 0.36     | 0.072    |
| $T_{1}^f$ [K] | 5665   | 5217     | 7246     |
| $T_{2}^f$ [K] | 3681   | 4928     | 5451     |
| $q(L)$      | 0.475   | 0.774    | 0.517    |
| $q(T^f)$    | 0.502   | 0.714    | 0.634    |
| $q_{fit}$   | 0.428   | 0.764    | 0.649    |

Fig. 4  The three synthetic fits used for determination of the precision of fitted parameters: illustration for the secondary relative radius of KIC 10518735 and orbital inclination of KIC 8111622.
and $\omega_0$ and $T_2$ around their initial values (3); inclination $i$ in the range 80-90° (appropriate for eclipsing detached stars); potentials $\Omega_{1,2}$ around their values corresponding to the initial values of $r_{1i}$ and $r_{2i}$ from equations (4). We adopted coefficients of gravity brightening 0.32 and reflection effect 0.5 appropriate for late stars (Table 1). The limb-darkening coefficients were chosen according to the tables of Van Hamme (1993).

After reaching the best fit (corresponding to the minimum of $\chi^2$) we adjusted the stellar temperatures $T_1$ and $T_2$ around the value $T_m$ (Table 1) by the formulae (Kjurkchieva and Vasileva 2015)

$$T_1^f = T_m + \frac{\Delta T}{s + 1},$$

$$T_2^f = T_1 - \Delta T,$$

where $s = L_2/L_1$ (luminosity ratio) and $\Delta T = T_m - T_2$ were taken from the last PHOEBE fitting.

Although PHOEBE works with potentials, it gives a possibility to calculate directly all values (polar, point, side, and back) of the relative radius $r_i = R_i/a$ of each component ($R_i$ is linear radius and $a$ is orbital separation). Moreover, PHOEBE yields as output parameters bolometric magnitudes $M_{bol}$ of the two components in conditional units (when radial velocity data are not available). But their difference $M_{bol}^2 - M_{bol}^1$ determines the true luminosity ratio $s = L_2/L_1$.

The parameters of the best light curve solutions are given in Table 2 while the corresponding synthetic curves are shown in Figs. 1–3 as continuous lines. The residual curves show bigger scatters during the eclipse phases (Figs. 1–3). Similar behavior could be seen also for other Kepler binaries (Hambleton et al. 2013a,b; Lehmann et al. 2013; Maceroni et al. 2010). It was attributed to the effects of finite integration time (Kipping 2010). The reasons for this effect may be also numerical imperfectness of the physical model (Prsa et al. 2016) as well as possible contribution of pulsations and spots.

The formal PHOEBE errors of the fitted parameters were unreasonably small. That is why we estimated the parameter errors manually based on the following rule (Dimitrov, Kjurkchieva and Iliev 2017). The error of parameter $A$ corresponds to that deviation $\Delta A$ from its best-fit value $A^{bf}$ for which the biggest residual (usually at the light curve minima) increases by $3\sigma$. The mean photometric errors $\sigma$ for KIC 8111622, KIC 10518735, KIC 8196180 are correspondingly 0.0004, 0.001, 0.0001.

Figure 4 illustrates our method for determination of precision of fitted parameters.
The errors of temperatures $T_i^f$ (calculated by equations 5–6) are around $\pm 200$ K and they are due mainly to the errors of $T_m$ (the errors of $T_2$ from PHOEBE are of order smaller, Table 2).

Besides the value $q(T^f)$ of mass ratio calculated by formula (3), we calculated its values $q(L)$ and $q(T^f)$ by the luminosity ratio $L_2/L_1$ from the PHOEBE solution and final component temperatures $T_i^f$ (Table 2). For our targets the foregoing values of the mass ratio differ by up to 25%. We made the following additional light curve solutions: (i) $q$ was fixed to value $q(L)$; (ii) $q$ was fixed to value $q(T^f)$; (iii) $q$ was varied arbitrarily and the obtained value $q_{fit}$ is given in Table 2. We established that the corresponding best light curve solutions for these values were with equal values of orbital parameters, temperatures and relative radii. Only the values of potentials were different. This result confirmed once again the insensitivity of the light curve solution of well detached eclipsing binary to the mass ratio as well as the faithfulness of the rest orbital and stellar parameters.

The analysis of the light curve solutions (Table 2) led to the following results:

(i) KIC 8111622 and KIC 10518735 undergo total eclipses while the eclipses of KIC 8196180 are partial; (ii) KIC 8111622 and KIC 10518735 have eccentricity above 0.5 while that of KIC 8196180 is considerably smaller. This result is in consistence with the expectation the shorter-period binary (Table 1) to have the smaller eccentricity; (iii) The components of targets are G and K stars, excluding the primary of KIC 8196180 that is early F star; (iv) The temperature difference of the components of KIC 8111622 and KIC 8196180 is considerable (1500 K and 1800 K respectively). (v) The secondaries of all targets are almost twice smaller in size than their primaries.

We compared (Table 3) our parameter values with those of Armstrong et al. (2014). The results are: (i) the primary temperatures coincide within the errors; (ii) our values of temperatures of secondaries of KIC 8111622 and KIC 8196180 are considerably smaller than those of Armstrong et al. (2014); (iii) Our values of the ratio of stellar radii for KIC 8111622 and KIC 10518735 are quite near to those of Armstrong et al. (2014) but the two values for KIC 8196180 are quite different (Table 3). We checked that the synthetic light curves corresponding to the parameter values of Armstrong et al. (2014) do not reproduce Kepler light curves of the targets. The bright example is KIC 8196180 with slightly eccentric orbit and very different eclipse depths (Fig. 3) for which Armstrong et al. (2014) have obtained equal component temperatures (Table 3).

3 Out-of-eclipse variability of the targets

The out-of-eclipse light of KIC 811162 and KIC 8196180 contain semi-regular oscillations (Fig. 5) which undergo long-term modulation with amplitudes up to 0.01 mag. Their shape as well as lack of strong periodicity seem to exclude pulsation explanation. This was confirmed by the periodogram analysis of the out-of-eclipse data that revealed bad-defined peak. The out-of-eclipse variability of this type implies a superposition of two periodic (or quasi-periodic) signals of similar frequency. That produces characteristic "beating": presence of single larger peaks followed by two smaller peaks. One may note the fast changes of the shape and amplitude of the out-of-eclipse variability of KIC 811162 and KIC 8196180.

3.1 Tidally-induced effects

Besides eclipses KIC 811162 and KIC 8196180 exhibit tidally-induced periastron features (Fig. 6).

According to the model of Kumar, Ao and Quataert (1995) the amplitude of the periastron feature depends on the separation of the objects and their masses while its shape depends on the orbit parameters. The contributions of different parameters on the shape, width and amplitude of the periastron feature were investigated by Dimitrov, Kjurkchieva and Iliev (2017).

The shape and parameters of tidally-induced periastron features of KIC 811162 and KIC 8196180 confirmed the theoretical predictions.

(a) The periastron feature of KIC 811162 is around 2 times narrower than that of KIC 8196180 (Fig. 6) due to its bigger eccentricity (fig. 4 of Dimitrov, Kjurkchieva and Iliev (2017)).

(b) The amplitude of feature of KIC 8196180 is almost 3 times bigger than that of KIC 811162. This is due to the considerably smaller period of KIC 8196180 and correspondingly to the bigger relative radii of components (fig. 4 of Dimitrov, Kjurkchieva and Iliev (2017) leading to bigger tidal interaction. Additional reason may be its higher temperature (Kumar, Ao and Quataert 1995).

(c) The tidally-induced periastron features have a "hook" shape consisting of two parts with almost the same widths: light increasing preceded by light trough (that coincides with the primary eclipse). This shape is expected for systems with $150^0 \leq \omega \leq 180^0$ (fig. 3.
Table 3  Comparison of our values of component temperatures and ratio of stellar radii (first three columns) with those of Armstrong et al. (2014) (last three columns).

| Kepler ID | \(\langle T_1 \rangle_1\) | \(\langle T_2 \rangle_1\) | \(r_{2}/r_1\)_1 | \(\langle T_1 \rangle_2\) | \(\langle T_2 \rangle_2\) | \(r_{2}/r_1\)_2 |
|----------|-----------------|-----------------|--------------|-----------------|-----------------|--------------|
| 811162   | 5665            | 3681            | 0.55         | 5897±369        | 4587±765        | 0.62         |
| 10518735 | 5217            | 4928            | 0.67         | 5216±357        | 4928±581        | 0.71         |
| 8196180  | 7246            | 5451            | 0.48         | 8222±2763       | 8225±2792       | 0.73         |

of Dimitrov, Kjurkchieva and Iliev (2017). The arguments of periastron \(\omega\) of our two targets (Table 2) fulfil this condition.

The periastron feature of KIC 811162 is hardly visible (Fig. 6), partially due to its faintness (Table 1). But the clear and well-visible tidally-induced periastron feature of KIC 8196180 means that it may be considered definitely as a heartbeat star of EB+HB subtype (Dimitrov, Kjurkchieva and Iliev 2017).

None of our targets reveals tidally-induced pulsations.

3.2 Spot activity

(a) The dominant period of the out-of-eclipse variability of KIC 811162 \(P_{\text{out}} = 6.728\) days is not harmonic of the orbital period \(P_{\text{orb}} = 15.488\) d. The ratio \(P_{\text{orb}}/P_{\text{out}} \sim 2.3\) is near, but differs from the ratio of pseudo-synchronous angular velocity and mean motion \(\Omega_{ps}/n \sim 2.74\) corresponding to \(e = 0.53\) of KIC 811162 (Hut 1981).

The amplitude of periastron feature of KIC 811162 is around 0.0007 in relative fluxes (Fig. 6) while the amplitudes of the total out-of-eclipse variations are up to 0.0015 (Fig. 5). This means that the amplitudes of the additional variations do not exceed 0.0008 (in relative flux). Probably, \(P_{\text{out}}\) presents rotational period of some of the target components and the observed additional out-of-eclipse variability (besides periastron feature) is due to variable spot visibility. Then the bad-defined peak of the Fourier transform may be considered as a result of differential rotation of the asynchronous component while the long-term modulation may be attributed to stellar activity cycles. The asynchronism of KIC 811162 is expected considering its high eccentricity and long orbital period.

The cycles of out-of-eclipse variability of KIC 811162 alternate between bigger-amplitude single-peaked shape and smaller-amplitude two-peaked shape (Fig. 5). Two spots on almost opposite longitudes of the asynchronous component could explain the two-peaked cycles. However, the single-peaked cycles cannot be reproduced by one spot if the highly-inclined configuration of KIC 811162 is coplanar (it would cause light variation whose light curve is flat during almost half a cycle, different from the observed one in Fig. 5). There are two possible alternatives: KIC 811162 is not a coplanar binary (expected for asynchronous system) with arbitrary spot location or KIC 811162 is coplanar binary with big almost polar spot.

(b) The amplitude of periastron feature of KIC 8196180 is around 0.004 (in relative fluxes) while the amplitudes of the total out-of-eclipse variations are up to 0.008. This means that the amplitudes of the additional variations do not exceed 0.004. The dominant period of the total out-of-eclipse variability is the orbital one that means the additional variability (besides the periastron feature) to be also with the orbital period. The two-peaked shape of the variations (Fig. 5) and their period imply rotational variability of synchronously-rotating component with two spots on almost opposite longitudes. The variable amplitudes and durations of the two waves per cycle may due to differential rotation and variable latitude of the spots.

4 Conclusions

This paper presents the results of determination of the orbits and parameters of stellar configurations of the eclipsing eccentric binaries KIC 811162, KIC 10518735 and KIC 8196180 on the basis of their Kepler data. KIC 8196180 turned out heartbeat star. The characteristics of its tidally-induced feature are consistent with the theoretical predictions. Moreover, KIC 8196180 exhibits out-of-eclipse light variations with the orbital period that may be attributed to spot(s) on synchronously rotating component. Besides hardly visible periastron feature KIC 811162 exhibits small-amplitude light variations whose period is around 2.3 times shorter than the orbital one. They could be attributed to spots on asynchronously rotating component. The asynchronism of KIC 811162 was expected taking into account its long orbital period.

The presented study adds new member to the family of heartbeat binaries and provides new data to search for dependencies of the tidally-induced effects of eccentric binaries on their orbital and stellar parameters.

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5 Appendix

1) Within the black-body approximation the relative fluxes at the bottom of the two eclipses are

\[
f_1 = \frac{\pi k_1^2 T_1^4 \pi k_2^2 T_1^4 - \pi k_2^2 T_1^4}{\pi k_1^2 T_1^4 + \pi k_2^2 T_2^4} \tag{7}
\]

\[
f_2 = \frac{\pi k_1^2 T_1^4}{\pi k_1^2 T_1^4 + \pi k_2^2 T_2^4} \tag{8}
\]

where \( k_i = R_i/d \), \( R_i \) is the stellar radius, \( d \) is target distance.

By introducing \( X = (r_2/r_1)^2 \), \( Y = (T_2/T_1)^4 \) and eclipse depths \( d_1 = 1 - f_1 \) and \( d_2 = 1 - f_2 \) one can obtain

\[
X = \frac{d_1}{1 - d_2}, \quad Y = \frac{d_2}{d_1}, \tag{9}
\]

that means

\[
T_2/T_1 = \left( \frac{d_2}{d_1} \right)^{1/4}. \tag{10}
\]

The expressions (7–8) refer to totally-eclipsed binary. For partial eclipses the corresponding expressions are

\[
f_1 = \frac{\pi k_1^2 T_1^4 + \pi k_2^2 T_1^4 - a \pi k_2^2 T_1^4}{\pi k_1^2 T_1^4 + \pi k_2^2 T_2^4} \tag{11}
\]

\[
f_2 = \frac{\pi k_1^2 T_1^4 + \pi k_2^2 T_1^4 - a \pi k_2^2 T_2^4}{\pi k_1^2 T_1^4 + \pi k_2^2 T_2^4} \tag{12}
\]

where \( a \) is the relative area of the secondary component covered at secondary eclipse \( 0 < a < 1 \). One can check that the expressions (11–12) lead to the same relation (10).

2) If one assumes that the target components are MS stars then empirical relations between stellar parameters are applicable. From \( L \sim M^4 \) and \( R \sim M^{3/4} \) one can obtain

\[
q = M_2/M_1 = (L_2/L_1)^{1/4} = [(R_2/R_1)^2(T_2/T_1)^4]^{1/4},
\]

i.e.

\[
q = (M_2/M_1)^{(3/4)(1/2)}(T_2/T_1) = q^{3/8}(T_2/T_1). \tag{14}
\]

As a result

\[
q = (T_2/T_1)^{8/5} \tag{15}
\]

and

\[
r_2/r_1 = R_2/R_1 = q^{3/4}. \tag{16}
\]

3) The primary eclipse ends at phase \( \varphi_e \) of outer contact of the stellar components that can be obtained from the approximate formula

\[
r_1 + r_2 \approx \sin(2\pi \varphi_e). \tag{17}
\]

For well detached binaries with narrow eclipses one may substitute \( \sin(2\pi \varphi_e) \) with \( 2\pi \varphi_e \). Thus, we obtained

\[
r_1 + r_2 = \pi w \tag{18}
\]

where \( w \) is the eclipse width in phase units.

Part of the considerations in the Appendix can be found in Kjurkchieva and Ivanov (2006), Ivanov, Kjurkchieva and Srinivasan (2010) and Kjurkchieva, Vasileva and Atanasova (2017).
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