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Orbital Parameters of the Eclipsing Detached *Kepler* Binaries with Eccentric Orbits

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Abstract

We present precise values of the eccentricity and periastron angle of 529 detached, eccentric, eclipsing stars from the *Kepler* Eclipsing Binary catalog that were determined by modeling their long cadence data. The temperatures and relative radii of their components as well as their mass ratios were calculated based on approximate values of the empirical relations of MS stars. Around one-third of the secondary components were revealed to be very late dwarfs, some of them possible brown dwarf candidates. Most of our targets fall below the envelope $P(1 - e^2)^{3/2} = 5$ days. The (e, P) distribution of the known eccentric binaries exhibits a rough trend of increasing eccentricity with the period. The prolonged and continuous *Kepler* observations allowed us to identify 60 new highly eccentric targets with $e > 0.5$.

Key words: binaries: eclipsing – stars: fundamental parameters – stars: solar-type – surveys

Supporting material: machine-readable tables

1. Introduction

It is generally supposed that the fragmentation of a molecular cloud core during its gravitational collapse primarily produces wide binaries. Empirical data reveal that the main-sequence binary systems typically have eccentric orbits (Duquennoy & Mayor 1991). But the majority of studies on binaries have focused on near circular orbits (Pichardo et al. 2005). Bate et al. (2002) argued that the reason eccentric binaries are poorly studied is that they tend to have long periods, which require prolonged observations. Large surveys such as ROTSE, MACHO, ASAS, SuperWASP, etc. were able to monitor stars for much longer periods of time, which led to the discovery of many new eccentric binaries. These new discoveries led to the transformation of these systems as just objects of celestial mechanics to important targets of modern astrophysics. They became probes for study of various tidal phenomena: mechanisms for circularization of orbits and synchronization of stellar rotation with orbital motion, impermanent mass transfer occurring close to the periastron (Sepinsky et al. 2007; Lajoie & Sills 2011), and apsidal motion.

The space mission *Kepler* (Borucki et al. 2010; Koch et al. 2010) with its extended and nearly uninterrupted data set led to the discovery of a great number of variable stars in the range 7–17 mag. Around 3000 of them were classified as eclipsing binaries (Prsa et al. 2011; Slawson et al. 2011; Kirk et al. 2016), a portion of which on eccentric orbits. One of the most amazing achievements of *Kepler* is the observational confirmation of faint tidally induced effects, namely brightening around the periastron and oscillations with harmonics of the orbital period, which were predicted theoretically by Kumar et al. (1995).

The recent *Kepler* discoveries of circumbinary planets orbiting eccentric stars (Doyle et al. 2011; Orosz et al. 2012a, 2012b; Welsh et al. 2012, 2015; Kostov et al. 2013, 2014, 2016a; Schwamb et al. 2013) inspired investigation of the orbital evolution and fate of these planets (Kostov et al. 2016b).

Catalogs of binary stars displaying apsidal motion have been collected by different authors during the past century, the latest of which (Petrova & Orlov 1999) contains 128 binary stars with measured periods of apsidal motion.

Bulut & Demircan (2007) compiled the physical parameters (including apsidal motion parameters) of 274 eclipsing binaries (150 of them candidates with incomplete photometric observations and undetermined eccentricities) with eccentric orbits based on three large sources: *Hipparcos* catalog (ESA 1997), the atlas of the (O–C) diagrams of Kreiner et al. (2001), and the ninth catalog of spectroscopic binary orbits (Pourbaix et al. 2004).

The available resources of the *Kepler* database make it a good candidate for the next study of eccentric binaries. The first EB (Eclipsing Binary) catalog (Prsa et al. 2011; Slawson et al. 2011) based on the *Kepler* data from the quarters Q0 and Q1 contains ephemeris (T_0, P), morphology type, $T_{\rm eff}$, $\log g$, $E(B - V)$, and third light (contamination) for around 2000 stars. For some of them, estimations are provided for the parameters T_2/T_1, q, $\sin i$, $(R_1 + R_2)/a$, $e \sin \omega$, and $e \cos \omega$.

Coughlin et al. (2011) modeled the light curves of 231 low-mass *Kepler* eclipsing binaries, some of them on eccentric orbits. Van Eylen et al. (2016) determined $e \cos \omega$ of 945 eclipsing *Kepler* binaries by measuring the relative timing of the primary and secondary eclipses.

Kirk et al. (2016) presented the final catalog of EB systems from the primary *Kepler* mission (Q0-Q17 Data Release) with around 3000 targets, as well as a list with 173 heartbeat stars and a list with 24 stars with tidally induced pulsations. But this catalog does not contain orbital parameters of the eccentric binaries.

There are many investigations of individual eccentric binaries (Frandsen et al. 2013; Gaulme et al. 2013, 2014, 2016; Borkovits et al. 2014; Maceroni et al. 2014; Helminiak et al. 2016; Rawls et al. 2016, etc.). We have also modeled several tens of eccentric *Kepler* systems and have determined precisely their orbital and stellar parameters (Dimitrov et al. 2012; Kjurkchieva & Vasileva 2015a, 2015b, 2016; Kjurkchieva et al. 2016a, 2016b; Dimitrov et al. 2017).

All previous investigations of *Kepler* binaries on eccentric orbits are either incomplete or inaccurate. In this paper, we present a complete list of *Kepler* eclipsing binaries with precise values of their eccentricities and periastron angles, using the same calculation technique.

Table 1
Information about the Targets from the EB Catalog

KIC	P	T_0	K_m	T_{eff}	w_1	w_2	d_1	d_2	φ_2
1026032	8.4604378	54966.77381	14.813	5715	0.0203	0.0201	0.0710	0.0270	0.5266
1995732	77.3627213	55049.45585	15.673	5163	0.0055	0.0067	0.0911	0.0621	0.4163
2305372	1.4046920	54965.954227	13.8210	5664	0.1320	0.1155	0.6900	0.1284	0.5020
2306740	10.306987	54966.42521	13.545	5647	0.0386	0.0209	0.3153	0.2950	0.5158
2307206	204.0313791	55086.53868	15.734	5342	0.0032	0.0019	0.3534	0.1969	0.5071
2437060	3.1871104	55000.890724	16.9880	4452	0.0769	0.0775	0.1141	0.0182	0.5039
2437149	18.7987347	55008.62182	17.628	5130	0.0131	0.0190	0.2338	0.1535	0.4885

Note. Values derived for the first time in this article are flagged in the full tabulation.

(This table is available in its entirety in machine-readable form.)

2. Our Sample

We reviewed the *Kepler* EB catalog (Prsa et al. 2011; Slawson et al. 2011; Matijevic et al. 2012) to search for detached eclipsing binaries with eccentric orbits. We gathered targets whose phase difference between the primary and secondary minimum differed from 0.5 (parameter "sep") and/or whose durations of the two eclipse minima (parameters "pwidth" and "swidth") were not equal. Moreover, we visually examined the folded curves of the candidates. Our main selection criteria were: (i) the light curve must have two eclipses, i.e., we excluded light curves with one eclipse (as that of KIC 03230227) and those with more than two eclipses (as that of KIC 7668648); (ii) the boundary between the eclipses and out-of-eclipse parts of the light curve must be well apparent (requirement for detached binary configuration as well as for precise determination of eclipse widths); (iii) the eclipse depths must be above 0.0001 in flux units; (iv) the parameter "sep" must differ from 0.5 by at least 0.0004 and/or the widths of the two eclipse minima must differ by at least 5%. We found 529 eclipsing detached binary stars that fulfill these criteria. Some of these were parts of more complex configurations that also contain planets or tertiary companions (see further targets in Tables 4–5).

Table 1 contains the available information for these systems (ordered by increasing KIC number) from the EB catalog where P is period (in days); T_0 is initial epoch (in BJD); the *Kepler* magnitude is K_m; target temperature is T_{eff}; $w_{1,2}$ is the width of the eclipses (in phase units); $d_{1,2}$ is the depth of the eclipses (in flux units); and the phase of the secondary eclipse is φ_2 (it is assumed $\varphi_1 = 0$). Some values of $w_{1,2}$ and $d_{1,2}$ were estimated first by us (flagged values in Table 1).

To determine the orbital eccentricity e and periastron angle ω of the targets, we used the code PHOEBE (Prsa & Zwitter 2005) for synthesis of the light curves of binary systems and long cadence (LC) data of targets (because the short cadence ones were small in numbers and had larger scatter). To ignore the effect of accidental light fluctuations and to accelerate the procedure, we binned all available LC data, usually with 1000 bins in phase (using a smaller value leads to loss of information from the eclipses).

Using the values of φ_2, w_1, and w_2 from Table 1 ($\varphi_1 = 0$) we calculated preliminary values e_0 and ω_0 by the formulae (Dimitrov et al. 2012)

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

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

Table 2
Stellar and Orbital Parameters of the Targets

KIC	T_1	T_2	q	r_1	r_2	e	ω
1026032	5715	4488	0.6630	0.0367	0.0270	0.042	353.24
1995732	5163	4691	0.8497	0.0092	0.0081	0.146	152.92
2305372	5664	3720	0.4894	0.2615	0.1530	0.023	289.00
2306740	5647	5554	0.9721	0.0612	0.0600	0.299	274.77
2307206	5342	4615	0.7799	0.0055	0.0046	0.151	84.61
2437060	4452	2814	0.4583	0.1551	0.0864	0.018	293.00
2437149	5130	4618	0.8363	0.0219	0.0192	0.029	238.13

Note. All flags are given in the full tabulation.

(This table is available in its entirety in machine-readable form.)

representing approximations of formulae (9–25) and (9–37) of Kopal (1978).

We used the available target temperatures T_{eff} (Table 1) from the *Kepler* Input Catalog (Brown et al. 2011) and adopted $T_1 = T_{\mathrm{eff}}$. For binaries with unknown T_{eff} (see blank places in Table 1) we assumed the mean (solar) value of 5800 K for the *Kepler* targets (flagged values in Table 2).

Based on the assumption that the stellar components are MS stars, we calculated approximate values of their parameters from empirical relations (Ivanov et al. 2010): secondary temperature $T_2 = T_1\ (d_2/d_1)^{1/4}$, mass ratio $q = (T_2/T_1)^{1.7}$, and ratio of relative radii $k = r_2/r_1 = q^{0.75}$. From the last formula and the approximate expression for narrow eclipses

$$r_1 + r_2 \approx \pi\bar{w}. \tag{3}$$

($\bar{w}$ is the mean eclipse width from Table 1) we derived approximate values of relative stellar radii:

$$r_1 = \frac{\pi\bar{w}}{(1+k)} \quad r_2 = \frac{\pi\bar{w}}{(1+k)}k. \tag{4}$$

The calculated values of T_2, q, r_1, and r_2 (first columns of Table 2) were used as fixed parameters for PHOEBE while the calculated values e_0 and ω_0 were used as input parameters. The orbital inclination i was fixed to correspond approximately to the individual eclipse depths. By varying e and ω around e_0 and ω_0 as well as "phase shift" we searched for the perfect coincidence of the phases of eclipses.

Our approach was based on the supposition that the orbital parameters e and ω do not correlate with the rest of the configuration parameters. To check this, we performed various tests. It turned out that models with different orbital inclination or with different ratios of radii but equal eccentricity fit equally well the phases of eclipses, i.e., the orbital parameters

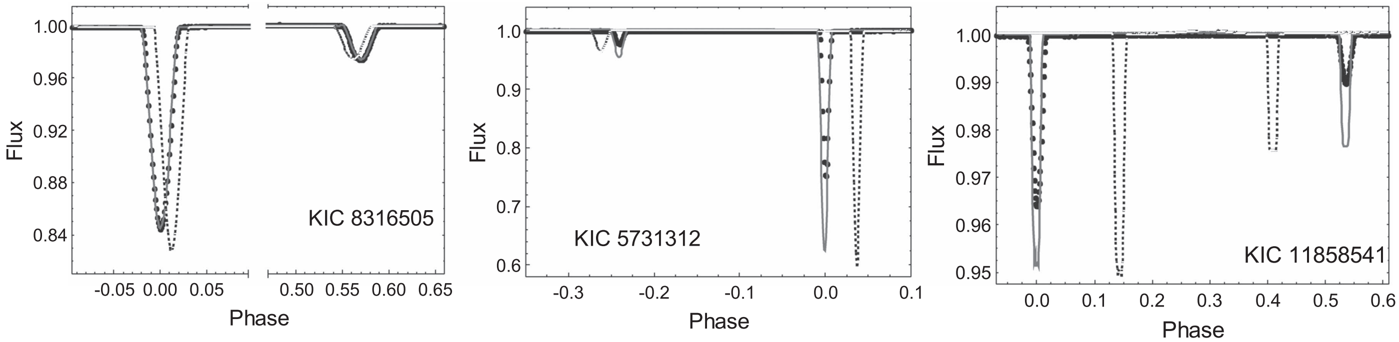

Figure 1. Illustrations of the results from our fitting procedure. Left panel: our excellent fit of KIC 8316505 (Kjurkchieva & Vasileva 2016) as a result of detailed modeling of its relatively wide eclipses; middle and right panels: examples of our partial light curve solutions (from this paper) of KIC 5731312 and KIC 11858541. The *Kepler* data are given with filled circles, our synthetic curves with continuous lines, while dashed lines reveal the synthetic curves corresponding to the orbital parameters of Prsa et al. (2011).

are independent of the rest configuration parameters. That is why we did not attempt to optimize the rest of the parameters, because this is a very time-consuming task for eccentric systems, while our goal was to obtain precise orbital parameters for a large sample. Nevertheless, the approximate values of the fixed parameters led to quite a good reproduction of eclipse widths, but not of eclipse depths (Figure 1, middle and right panels). The comprehensive light curve solution provides an excellent reproduction of the data (Figure 1, left panel) but needs much more time. It is appropriate for the precise study of small samples.

Our results for e and ω are shown in the last two columns of Table 2. Their precision is correspondingly better than 0.1% for $e > 0.1$, 1% for $e < 0.1$ and $\sim$10% for $e < 0.01$.

Some targets of our sample have been studied previously, so we provide comparison of our orbital parameters with the previous ones.

(1) Most of our values of e and ω differ substantially from those of Prsa et al. (2011) and Figure 1 illustrates that solutions with their values do not reproduce the photometric data. Van Eylen et al. (2016) noted that the values of eccentricity in the EB catalog are not precise enough, presumably because the neural-network approach (Prsa et al. 2008) has been designed to measure many different properties for a wide variety of binary stars.

(2) Coughlin et al. (2011) modeled double-eclipse, detached binary systems by the JKTEBOP code and determined their e and ω with precision 0.01 and 1°. Our results for e and ω are very close to those of Coughlin et al. (2011) for the common targets.

(3) Dong et al. (2013) determined the quantity e_{min} for 15 long-period (40–265 days) eclipsing *Kepler* binaries on highly eccentric orbits (e between 0.5 and 0.85) based on their closely separated primary and secondary eclipses. Our eccentricities turn out to be equal or bigger than those of Dong et al. (2013), i.e., their values do refer to the lower limits of target eccentricity.

(4) Helminiak et al. (2016) presented simultaneous light and radial velocity curve solutions of detached eclipsing binaries using JKTEBOP. Our values of eccentricity are close to theirs (see Table 3). The two sets of values of the periastron angle of KIC 08430105 and KIC 10001167 differ by 180°. Such a "180° ambiguity" in ω was discussed earlier for HB stars (Dimitrov et al. 2017).

(5) Borkovits et al. (2015) reported eclipse timing variation analyses of 26 compact hierarchical triple stars comprised of an eccentric eclipsing binary and a relatively close tertiary component found in the *Kepler* field. Five of them do not fulfill our requirements (they have three or more light minima). Table 4 presents two sets of parameters for the "inner" binary of the common targets.

According to Mazeh & Shaham (1979), a distant companion prevents circularization of binary orbit by inducing a long-term eccentricity (and plane motion) modulation, which may trigger transient mass transfer and other astrophysical effects in the

Table 3
Comparison with Orbital Parameters of Helminiak et al. (2016)

Target	e_H	ω_H	$e_{\rm our}$	$\omega_{\rm our}$
KIC 03120320	0.034	343	0.049	43.14
KIC 08430105	0.256	350.5	0.253	168.80
KIC 10001167	0.160	213	0.154	28.59

(This table is available in machine-readable form.)

Table 4
Comparison with Orbital Parameters of Borkovits et al. (2015)

Target	e_B	ω_B	$e_{\rm our}$	$\omega_{\rm our}$
4940201	0.001	194–202	0.0458	271.97
5653126	0.272	307–312	0.210	149.96
6545018	0.003	180–225	0.0025	35.01
7812175	0.16	326–328	0.141	164.29
8023317	0.251	178–175	0.278	332.50
8210721	0.142	156–159	0.148	333.51
8938628	0.003	345–351	0.003	130.41
9714358	0.015	142–379	0.085	81.19
5771589	0.013	236–457	0.077	93.97
7955301	0.031	117–201	0.151	80.25
5003117	0.145	308–309	0.101	207.67
5731312	0.42	184	0.431	14.15
7670617	0.246	136–138	0.195	23.74
8143170	0.146	291–293	0.081	132.49
9715925	0.201	354	0.205	165.20
9963009	0.224	258–257	0.049	346.56
10268809	0.314	143–145	0.281	25.26
10319590	0.026	249–254	0.028	67.68
10979716	0.074	106–108	0.042	301.44
11519226	0.187	359–360	0.189	169.49
12356914	0.403	108	0.420	72.78

(This table is available in machine-readable form.)

Table 5
Orbital Parameters of Eclipsing Binary Stars with Transiting Circumbinary Planet

KIC	Other Name	e_{pr}	ω_{pr}	Source	e_{our}	ω_{our}
12644769	Kepler-16	0.159	92.35	Doyle et al. (2011)	0.186	95.30
8572936	Kepler-34	0.521	300.20	Welsh et al. (2012)	0.597	64.70
9837578	Kepler-35	0.142	89.18	Welsh et al. (2012)	0.063	81.85
6762829	Kepler-38	0.103	268.68	Orosz et al. (2012b)	0.146	91.23
10020423	Kepler-47	0.023	212.30	Orosz et al. (2012a)	0.048	245.50
4862625	Kepler-64	0.222	221.14	Schwamb et al. (2013)	0.174	164.12
12351927	Kepler-413	0.037	279.54	Kostov et al. (2014)	0.138	266.50
9632895	⋯	0.051	262.86	Welsh et al. (2015)	0.050	264.62
5473556	Kepler-1647	0.159	300.85	Kostov et al. (2016a)	0.137	53.08

(This table is available in machine-readable form.)

system: shrink to very short orbits, coalesce, supernova explosion, etc. (Kostov et al. 2016b). However, the variations of eccentricity are with a period of the order of ten years and have small amplitudes. We established that they do not cause an apparent effect on the binned *Kepler* data, nor correspondingly on the light curve solutions. That is why we did not analyze eccentricity variations. Nevertheless, we suppose that the differences between the two sets of parameters in Table 4 may be due (at least partially) to the long-term modulation of orbital parameters.

(6) The values $e\cos\omega$ of Van Eylen et al. (2016) are equal to ours for the common targets.

(7) Gaulme et al. (2013, 2014, 2016) studied red giants in eclipsing *Kepler* binaries. Around 60 targets turned out to have detached configurations with eccentric orbits, but the light curves of some of them do not fulfill our requirements. Our orbital parameters for the common targets are (very) close (or with "180° ambiguity" in ω) to theirs, determined by JKTEBOP.

(8) Several targets of our sample are configurations of binary stars and a transiting circumbinary planet. Table 5 shows the orbital parameters of their binary star orbits from previous authors (e_{pr}, ω_{pr}) and our values. It is expected that the presence of a planet around the binary star will cause perturbations of eclipse times (Doyle et al. 2011), but this effect is not apparent on the binned *Kepler* data, and we have not studied it.

Finally, we provide a comparison with the results of individual binaries investigated earlier in detail.

Frandsen et al. (2013) obtained $e = 0.689$ and $\omega = 300^\circ.83$ for KIC 8410637, while our values are $e = 0.609$ and $\omega = 128^\circ.84$ (again with "180° ambiguity").

There is a small difference between the values $e = 0.05$ and $\omega = 37^\circ.26$ of Borkovits et al. (2014) for KIC 8560861 and our values $e = 0.039$ and $\omega = 20^\circ.3$.

By simultaneous photometric and radial velocity solution, Rawls et al. (2016) obtained for KIC 9246715: $e = 0.356$; $\omega = 18^\circ$; $q = 1$. Our values are close: $e = 0.349$; $\omega = 13^\circ.6$; $q = 0.824$.

On the base of simultaneous photometric and radial velocity solution, Maceroni et al. (2014) obtained for KIC 3858884: $e = 0.465$; $\omega = 21^\circ.61$; $q = 0.988$; $r_2/r_1 = 0.888$. Our values are almost the same: $e = 0.458$; $\omega = 22^\circ.04$; $q = 0.915$; $r_2/r_1 = 0.934$.

3. Statistical Analysis of Results

The eccentric *Kepler* binaries from our sample have periods in the wide range of 1–1087 day (see Table 1). Their distribution is as follows: 10 targets have $P > 500$ days; 23 with $500 > P > 200$ days; 33 with $200 > P > 100$ days, 11 with $100 > P > 75$ days; 37 with $75 > P > 50$ days; 38 with $50 > P > 35$ days; 79 with $35 > P > 20$ days; 123 with $20 > P > 10$ days; 95 with $10 > P > 5$ days; 62 with $5 > P > 2$ days; and 18 with $2 > P > 1$ day.

The low temperatures ($T_2 < 3700$ K) of around one-third of the secondaries of our sample (Table 2) need additional consideration. In fact, the values $T_{1,2}$ in Table 2 are underestimated because we have assumed $T_1 = T_{\rm eff}$ while the real value of T_1 is usually bigger than $T_{\rm eff}$ (and $T_2 < T_{\rm eff}$) and correspondingly the real value of T_2 is bigger than that calculated by the expression $T_2 = T_1\ (d_2/d_1)^{1/4}$. Taking into account this effect, we estimated that the reliable values of T_2 are larger than the values in Table 2 usually by around 100 K, and very seldom by up to 300 K. Moreover, one should remember that the precision of determination of $T_{\rm eff}$ is ± 200 K (Brown et al. 2011).

The *Kepler* binaries have eccentricities in the wide range of 0.001–0.85 (see Table 2). Their distribution is as follows: 3 targets are with $e > 0.8$ (the biggest value is $e = 0.845$); 9 with $0.8 > e > 0.7$; 14 with $0.7 > e > 0.6$, 34 with $0.6 > e > 0.5$; 49 with $0.5 > e > 0.4$; 71 with $0.4 > e > 0.3$, 84 with $0.3 > e > 0.2$; 106 with $0.2 > e > 0.1$; 141 with $0.1 > e > 0.01$; and 18 with $0.01 > e > 0.001$.

Hence, 60 new highly eccentric targets with $e > 0.5$ were found by *Kepler*. For comparison, the catalog of Bulut & Demircan (2007) of 124 members contains 22 targets with $e > 0.3$ and only 2 targets with $e > 0.5$.

Period–eccentricity is one of the most interesting and debatable relations of the eccentric binaries. Various attempts have been made in the past to explain the observed trend that the binaries with longer periods have larger eccentricities: tidal action (Russell 1910), secular decrease in the stellar mass (Jeans 1924), effect of encounters (Walters 1932a, 1932b), to name a few. 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 theoretical dependence period–eccentricity $PM^2e^{-6}(1 - e^2)^{3/2} = \mathrm{const}$ that has been confirmed by parameters of binaries with periods $P \geqslant 5$ days (Mayor & Mermilliod 1984). Mathieu et al. (1990) obtained similar results for eight evolved MS binaries belonging to the old open cluster M67, but determined a cutoff period of around 11 days. Almost the same value was obtained by Raghavan et al. (2010).

Based on the investigations of tidal interaction by Zahn (1977) and Mazeh & Shaham (1979), Duquennoy & Mayor (1991) concluded that the orbital period generally decreases

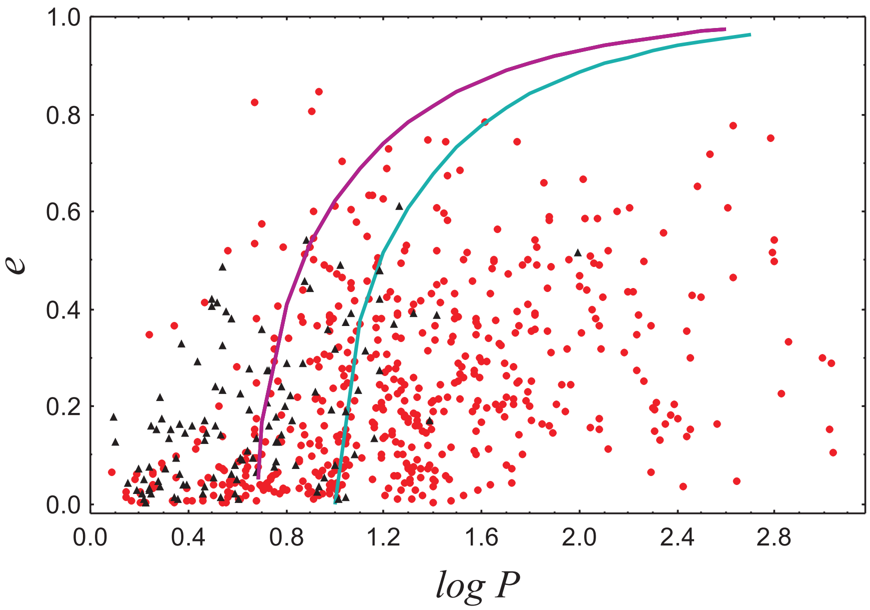

Figure 2. Diagram period–eccentricity of eccentric binaries: (black) triangles for the sample of Bulut & Demircan (2007), (red) circles for targets of this paper, continuous (green and violet) lines describe tracks of constant angular momentum $P(1 - e^2)^{3/2}$ corresponding to 10 days and 5 days, respectively.

with e^2. The evolutional decay of the eccentricity is associated with energy dissipation and changes in orbital axis.

We built a common (P, e) diagram for our homogeneous sample (Figure 2). Most of our targets (excluding several tens with small periods) fall below the envelope $P(1 - e^2)^{3/2} = 5$ days while most of the members of the catalog of Bulut & Demircan (2007) fall to the left of this line. Figure 2 reveals a faint trend of eccentricity increasing with the period.

Our results do not confirm the assumption of Van Eylen et al. (2016) that at the shortest periods, hot–hot binaries are more likely to be eccentric than hot–cool or cool–cool systems.

4. Conclusion

This paper presents the results of precise determination of the orbital parameters of eccentricity and periastron angle for 529 eccentric eclipsing binaries based on *Kepler* data. We also calculated approximate values of temperatures and relative radii for the target components based on empirical relations of MS stars. Around one-third of the secondaries turned out to be very late dwarfs, some of them possible brown dwarf candidates.

The common (P, e) diagram of the known eccentric binaries from the catalog of Bulut & Demircan (2007) and *Kepler* EB catalog revealed a poorly expressed trend of eccentricity increasing with the period.

The obtained values of the eccentricities and periastron angles of a large sample of eclipsing binaries could be used for future studies of apsidal motion and tidal phenomena.

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