Serb. Astron. J. № 195 (2017), 33 - 39
DOI: https://doi.org/10.2298/SAJ1795033K

UDC 524.386
Original scientific paper

LIGHT CURVE SOLUTIONS AND OUT-OF-ECLIPSE VARIABILITY OF KIC 10031409, KIC 11228612, KIC 11403216 AND KIC 11913071

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(Received: June 8, 2017; Accepted: September 13, 2017)

SUMMARY: We carried out light curve solutions of four detached binaries observed by *Kepler*. As a result, their orbital inclinations, temperatures and relative stellar radii were determined. KIC 10031409 and KIC 11228612 reveal partial eclipses while the components of KIC 11403216 and KIC 11913071 undergo total eclipses. The secondary component of KIC 11403216 is probably a very late M dwarf or brown dwarf. The out-of-eclipse brightness of KIC 10031409, KIC 11228612 and KIC 11913071 vary with the orbital period and might be explained by spots on synchronously-rotating star(s). The out-of-eclipse variability of KIC 11403216 is with a period that is a third of its orbital period and may be due to spot on asynchronous rotating component. The resonance 1:3 needs future study of KIC 11403216.

Key words. binaries: close – binaries: eclipsing – Methods: data analysis – Stars: fundamental parameters – Stars: individual: KIC 10031409, KIC 11228612, KIC 11403216, KIC 11913071

1. INTRODUCTION

The study of stellar structure and evolution requires rich statistics of binaries with precise global parameters. The space mission *Kepler* provided extended and nearly uninterrupted data set for a variety of variable stars. An automated fitting of these data was used for initial classification of the variability. Thus, nearly three thousand eclipsing binaries (EBs) were identified and included into the *Kepler* EB catalog (Prsa et al. 2011, further Paper I; Slawson et al. 2011, Matijevic et al. 2012, Kirk et al. 2016). Most of the unprecedentedly precise *Kepler* data are available to astronomical community and some individual *Kepler* EBs became objects of detailed study. Moreover, the light curve solutions of the *Kepler* data allowed precise investigation of out-of-eclipse variability due to spots and flares (Mathur et al. 2014, Arkhypov et al. 2015, Kjurkchieva et al. 2016a).

This paper is a continuation of our study of detached binaries based on *Kepler* data (Kjurkchieva and Vasileva 2015, Kjurkchieva et al. 2016a,b,c,d,e, Dimitrov et al. 2017). It presents light curve solutions of four eclipsing detached binaries aiming to determination of parameters as well as analysis of out-of-eclipse variability.

2. TARGETS

There are many hundreds of detached eclipsing binaries in the *Kepler* EB catalog. Most of them have long periods and correspondingly short eclipses (in phase units). We have chosen to model four unexplored systems whose eclipses have durations above 0.03 (in phase units) allowing precise solutions. Moreover, these targets exhibit out-of-eclipse variability deserving detailed analysis.

Table 1. Parameters of the targets from the EB catalog: *Kepler* magnitude m_K; orbital period P in days; target temperature T_m in K; depth of the primary and secondary eclipses $d_{1,2}$ (in flux units); mean eclipse width w (in phase units).

Star	m_K	P	T_m	d_1	d_2	w
KIC 10031409	13.553	4.1438796	5905	0.1884	0.1790	0.039
KIC 11228612	14.647	2.9804799	5829	0.3486	0.0783	0.046
KIC 11403216	15.537	4.0532529	5757	0.1033	0.0031	0.034
KIC 11913071	9.532	3.7478351	8329	0.1890	0.0467	0.055

The stars KIC 10031409 (≡ 2MASS J19544436+4656598), KIC 11228612 (≡ 2MASS J18502573+4858057), KIC 11403216 (≡ 2MASS J19280645+4912258) and KIC 11913071 (≡ 2MASS J19241473+5015196 ≡ HAT 199-30766, V2365 Cyg) have been suspected as potential transit signal sources during the first quarters of the *Kepler* mission (Tenenbaum et al. 2012). Further, they were flagged as "False Positives" and classified as eclipsing binaries of Algol type (Paper I). Table 1 presents available information about the targets from the EB catalog. The targets have long-cadence (LC) data from almost all quarters. KIC 11913071 has also short cadence (SC) data covering parts of quarters Q3 and Q4.

3. LIGHT CURVE SOLUTIONS

We carried out the modeling of our data by using the package PHOEBE (Prsa and Zwitter 2005) based on the Wilson–Devinney code (Wilson and Devinney 1971). It is appropriate for our task because it allows us to model data in various filters, including those of *Kepler* (Hambleton et al. 2013a). The observational data (Fig. 1) show that our targets are detached systems. That is why we modelled them using the mode "Detached binary".

To ignore the effect of accidental light fluctuations in the procedure of the light curve solutions, we modelled all available LC data (above 50000 points for each target) after appropriate phase binning. For this purpose we applied the PHOEBE option for binning of data with 1000 bins in phase (the smaller value leads to loss of information from the eclipses).

We used the data from *Kepler* Eclipsing Binary Catalog – Third Revision (Matijevic et al. 2012, *keplerebs.villanova.edu*). These data were detrended for instrumental drifts. We have not carried out additional detrending, particularly to remove light fluctuations caused by spots, pulsations, periastron effects, etc. We have done only phasing of the data on the orbital period from Table 1 and binning of the phased data.

The procedure of the light curve solutions consists of several steps. Firstly, we adopted the primary temperature $T_1 = T_m$ and assumed that the stellar components are MS stars. Then we calculated the initial (approximate) values of the secondary temperature T_2, mass ratio q, relative stellar radii r_1 and r_2, based on empirical relations of MS stars (Ivanov et al. 2010): $T_2 = T_1(d_2/d_1)^{1/4}$, $q = (T_2/T_1)^{1.7}$; $k = r_2/r_1 = q^{0.75}$. As the fourth equation we used the approximate relation for narrow eclipse (Kjurkchieva and Vasileva 2018)

$$r_1 + r_2 \approx \pi w \,, \quad (1)$$

where w is the eclipse width from Table 1.

Further, we searched for the best fit by varying: T_2 and q around their initial values; orbital inclination i in the range 70-90° (condition for eclipsing detached stars); potentials $\Omega_{1,2}$ around their values corresponding to the initial values of r_1 and r_2. 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 solution (corresponding to the minimum of χ^2) we adjusted the stellar temperatures T_1 and T_2 around the value T_m by formulae (Kjurkchieva and Vasileva 2015):

$$T_1^f = T_m + \frac{c\Delta T}{c+1} \,, \quad (2)$$

$$T_2^f = T_1^f - \Delta T \,, \quad (3)$$

where the quantities $c = l_2/l_1$ (the ratio of the relative luminosities of the stellar components) and $\Delta T = T_m - T_2$ are determined from the PHOEBE solution.

Table 2. Fitted parameters of the best light curve solutions.

Star	i	q	T_2	Ω_1	Ω_2
KIC 10031409	86.0(0.6)	0.486(0.007)	5769(15)	10.865(0.009)	9.279(0.006)
KIC 11228612	87.2(0.7)	0.742(0.005)	4342(16)	10.211(0.007)	11.906(0.007)
KIC 11403216	85.9(0.3)	0.274(0.003)	3006(40)	9.373(0.009)	9.132(0.006)
KIC 11913071	85.8(0.4)	0.481(0.003)	5770(32)	7.636(0.005)	9.306(0.004)

Table 3. Calculated parameters.

Star	T_1^f	T_2^f	r_1	r_2	l_2/l_1
KIC 10031409	5925	5830	0.096(0.003)	0.061(0.004)	0.347
KIC 11228612	6038	4013	0.105(0.002)	0.069(0.002)	0.133
KIC 11403216	5782	2396	0.110(0.003)	0.035(0.001)	0.007
KIC 11913071	8428	5872	0.140(0.002)	0.060(0.003)	0.042

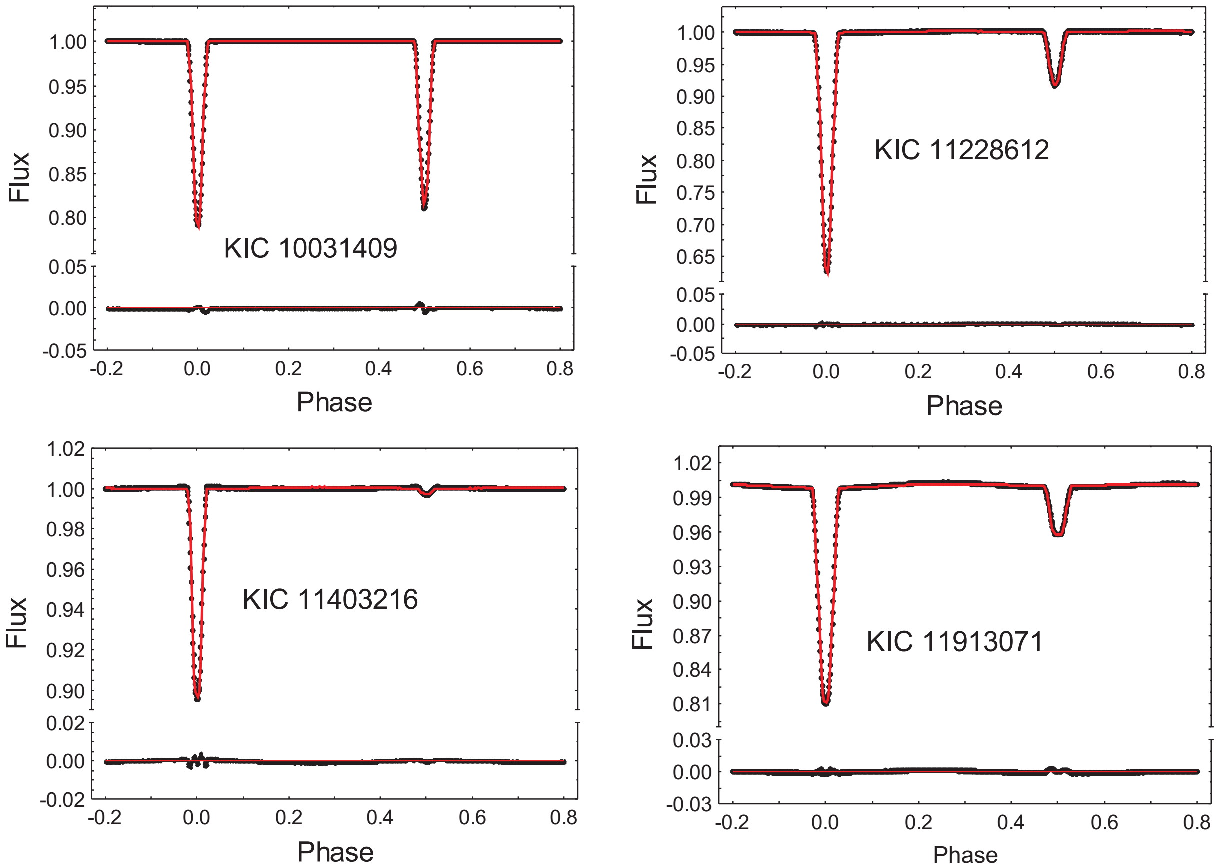

Fig. 1. *Top of each panel: the folded light curve from the* Kepler *archive and its* PHOEBE *fit; bottom of panel: the corresponding residuals.*

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 $M^i_{\rm bol}$ of the two components in conditional units (when radial velocity data are not available). But their difference $M^2_{\rm bol} - M^1_{\rm bol}$ determines the true luminosity ratio $c = L_2/L_1 = l_2/l_1$.

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 et al. 2017). The error of parameter b corresponded to that deviation Δb from its final value b^f for which the mean residuals increase by $3\bar{\sigma}$ ($\bar{\sigma}$ is the mean photometric error of the target).

Table 2 contains the final values of the fitted stellar parameters and their uncertainties: inclination i; mass ratio q; potentials $\Omega_{1,2}$; secondary temperature T_2. Table 3 exhibits the calculated parameters: stellar temperatures $T^f_{1,2}$; relative stellar radii $r_{1,2}$ (back values); ratio of relative stellar luminosities l_2/l_1. Their errors are determined from uncertainties of fitted parameters used for their calculation.

The synthetic curves corresponding to the parameters of our light curve solutions are shown in Fig. 1 as continuous lines. The residual curves show higher scatter during the eclipse phases. A similar behavior could also be seen for other *Kepler* binaries (Hambleton et al. 2013a, Hambleton et al. 2013b, Lehmann et al. 2013, Maceroni et al. 2014). It was attributed to the effects of finite integration time (Kipping 2010). The reasons for this effect may also be numerical imperfectness of the physical model

(Prsa et al. 2016) as well as contribution of pulsations and spots.

The main results from our light curve solutions of the eclipsing binaries KIC 10031409, KIC 11228612, KIC 11403216 and KIC 11913071 are as follows.

(1) The sum of their relative radii, $r_1 + r_2$, is within the range 0.15–0.20, i.e. they are well-detached systems.

(2) KIC 10031409 and KIC 11228612 reveal partial eclipses while the components of KIC 11403216 and KIC 11913071 (differing considerably in radius) undergo total eclipses. Hence, their mass ratios should be considered with high confidence (Terrell and Wilson 2005).

(3) The components of KIC 10031409 and KIC 11228612 are of the G–K spectral type.

(4) The high temperature of the primary component of KIC 11913071 (Table 2) is in consistency with the estimation of Sokoloski and Stone (2000) who discovered the eclipsing binary nature of this star and determined its spectral type as A5. The relatively big temperature difference of the components (nearly 2500 K) explains the visible contribution of the reflection effect in the out-of-eclipse part of the KIC 11913071 light curve (Fig. 1).

(5) The secondary component of KIC 11403216 is a late M dwarf (or maybe brown dwarf). Although the temperature difference of target components is 2760 K there is no visible reflection effect in the out-of-eclipse part of light curve. This could be explained by a negligible contribution of the secondary star to the common luminosity (0.7 %). The faint light increase around the eclipses (the so called "volcano effect") probably is an artefact due to the automatic reduction procedure of the *Kepler* data (Kjurkchieva et al. 2016b).

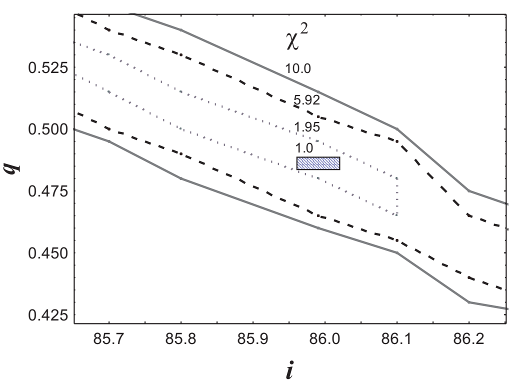

Fig. 2. *Illustration of the* q*-search analysis for KIC 10031409: the different isolines circumscribe the areas whose normalized* χ^2 *are smaller than the marked values; the empty circle corresponds to the final value of the mass ratio and orbital inclination given in Table 2.*

(6) The mass ratios q of the binaries are within a wide range 0.27–0.74. The PHOEBE values for totally-eclipsed targets could be accepted with confidence. For partially-eclipsed targets we carried out additionally the q-search analysis (Dimitrov and Kjurkchieva 2015) to check the effect of correlation between the mass ratio and orbital inclination (suspected from the correlation matrix). For this purpose we fixed all configuration parameters except for i and q. The last ones were varied by a fine grid and the corresponding normalized χ^2 values were calculated. Fig. 2 illustrates the q-search procedure for KIC 10031409. It reveals the correctness of the obtained i and q as well as their precision.

4. OUT-OF-ECLIPSE VARIABILITY

The ground-based observations have many gaps and do not allow precise investigation of the spot and flared activity of the stars. This problem was overcome with the space missions as *MOST* (Guenther et al. 2008), *CoRoT* (Affer et al. 2009) and *Kepler*, producing prolonged and precise observations. Their data could be used for intensive study of the stellar activity.

The high-precise *Kepler* data of our targets allowed us to analyze their small-amplitude out-of-eclipse light variabilities. Fig. 3 exhibits their regular cycles whose amplitudes are modulated with scales of the order of several tens days. We carried out a periodogram analysis of the data using the PERIOD04 software package (Lenz and Breger 2005). For this purpose we used the original (detrended and nonphased) data whose eclipse points were removed. The periodograms (Fig. 4) confirmed cyclic nature of the out-of-eclipse light variations of all targets. The results of the time-series analysis are as follows.

(1) The out-of-eclipse cycles of KIC 10031409 are with the orbital period (Fig. 4) and consist of two waves with different amplitudes (Fig. 3) whose minima almost coincide with the eclipses. The shape of the observed small-amplitude variations and their period imply rotational variability of a synchronously-rotating component with surface inhomogeneities. Cool spot with angular size of the order of 10° may reproduce the observed amplitudes of out-of-eclipse light variations of KIC 10031409. But, if the system is coplanar (reasonable for a synchronous state) one spot on the component of a highly-inclined configuration would cause light variation whose shape is flat during almost half a cycle, different from the observed case. The two-waved shape of the small-amplitude light variations may be reproduced by two almost diametrically opposed cool spots on one of the KIC 10031409 components. Hence, the two-waved shape of variability means two diametrically-opposed longitudes of stellar spots, the so called flip-flop effect. Another alternative is to suppose variability from both components of KIC 10031409.

The long-term variability (amplitude modulation) may be due to cycles of stellar activity. The different amplitudes and durations of the two waves per cycle (Fig. 3) may be explained by differential rotation of the synchronous star(s) and variable latitude of the spot(s).

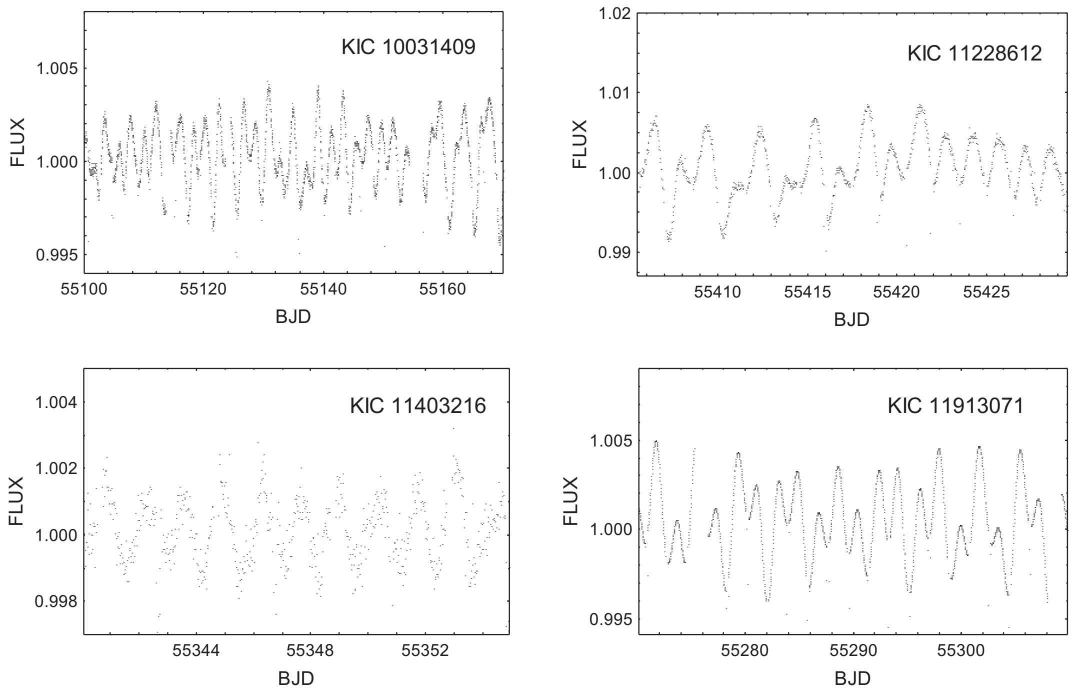

Fig. 3. *Several consecutive cycles of out-of-eclipse variability of the targets.*

(2) The cycles of KIC 11228612 are with orbital period (Fig. 4) and consist of two waves with different amplitudes, similarly to those of KIC 10031409. This behavior may be explained also by different spot visibility and synchronous rotation. The cycles with almost equal two waves have smaller amplitudes than those with unequal two waves (Fig. 3).

(3) The cycles of KIC 11403216 consist of almost equal waves with duration of 1.33355 d, a value just 3 times shorter than the orbital period (Fig. 4). This behavior may be explained by a near-polar spot on the asynchronously-rotating stellar component. Such a supposition is allowable for a wide binary. The resonance 1:3 deserves a special attention and investigation.

(4) The cycles of KIC 11913071 are with orbital period (Fig. 3) and consist of two waves with different amplitudes, similarly to those of KIC 10031409 and KIC 11228612. The amplitudes of the two waves change within several consecutive orbital cycles (Fig. 3) which may mean a short cycle of stellar activity. The orbital frequency $f_{\rm orb} = 0.26681532$ cycles/day is the second peak in amplitude of the periodogram (Fig. 4) while the highest peak corresponds to $2f_{\rm orb}$. The SC data of KIC 11913071 confirmed this result.

(5) We found several flare-like events of KIC 11403216 and KIC 11913071, similar to those detected for KIC 6697716 (Kjurkchieva and Atanasova 2016a). Although their durations and amplitudes are of the order smaller than the flares registered by Walkowicz et al. (2011), Balona (2012, 2013), Roettenbacher et al. (2013), Shibayama et al. (2013), Candelaresi et al. (2014), Maehara et al. (2015), they could be considered as other appearance of faint stellar activity of KIC 11403216 and KIC 11913071.

In principle, the stellar activity is an inherent characteristic of cool stars. Hence, it is reasonable to suppose that the spots and flare-like events are probably associated with the secondary components of our targets.

(6) The out-of-eclipse variability implies that three of our targets are synchronous systems. Their minimum ages could be estimated by the time of synchronization of stars with convective envelopes calculated by the approximate expression (6.1) $t_{\rm sync} \sim q^{-2}r^{-6}$ of Zahn (1977). In this way we obtained values 5.4 Myrs, 1.35 Myrs and 0.57 Myrs correspondingly for KIC 10031409, KIC 11228612, and KIC 11913071. For KIC 11403216 the time of synchronization is 7.5 Myrs, i.e. bigger than that of the other targets. Then, the asynchronous state of its component(s) derived from the out-of-eclipse variability seems explainable.

The calculation of $t_{\rm sync}$ by the precise formula (4.12) of Zahn (1977) required apsidal motion constant. Using $k \approx 0.004$ for low-mass stars (Jeffery 1984) we obtained considerably bigger values of $t_{\rm sync}$ (for instance, for KIC 10031409, it was 90 Myrs).

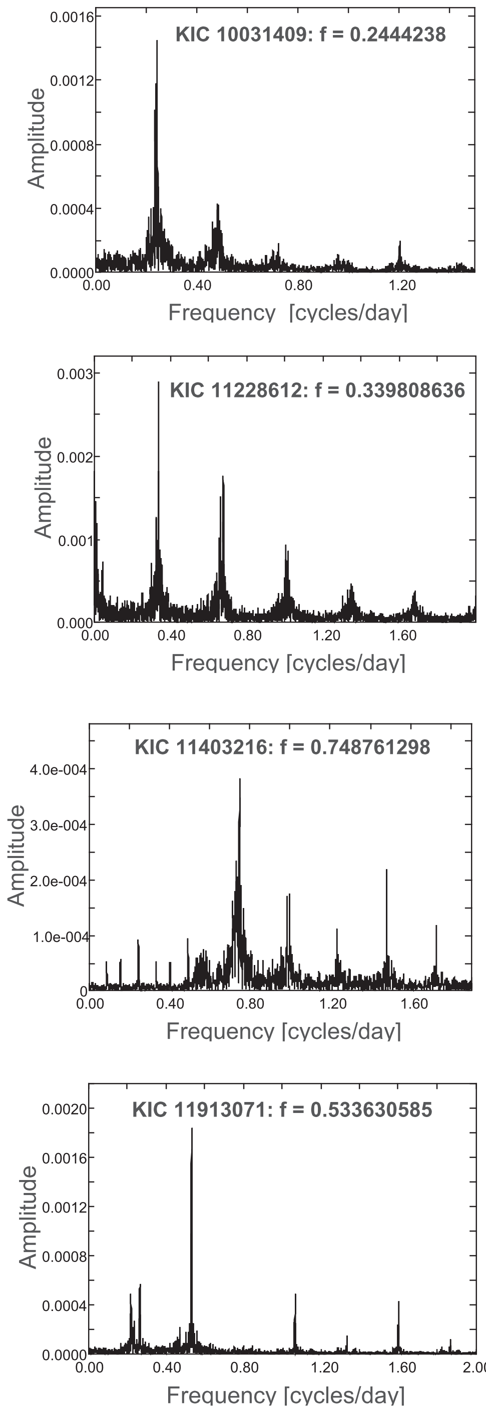

Fig. 4. *Periodograms of the targets.*

5. CONCLUSION

As a result of light curve solutions of four detached binaries observed by *Kepler* we determined their orbital inclinations, temperatures and relative stellar radii. KIC 10031409 and KIC 11228612 reveal partial eclipses while the components of KIC 11403216 and KIC 11913071 undergo total eclipses. The secondary component of KIC 11403216 turned out to be a late M dwarf or brown dwarf. Besides eclipses the targets exhibit cyclic small-amplitude variabilities. Those of KIC 10031409, KIC 11228612 and KIC 11913071 are with orbital period and might be explained by spots on synchronously-rotating star. The variability of KIC 11403216 is with a third of the orbital period and may due to near-polar spot on asynchronously-rotating star. This resonance 1:3 deserves future observations and investigation.

Acknowledgements – This work was supported partly by projects DN08/20 and DM08/02 of Scientific Fundation of the Bulgarian Ministry of Education and Science as well as by project RD 02-102 of Shumen University. We worked with the live version of the *Kepler* EB catalog (*http://keplerebs.villanova.edu/*). The authors are very grateful to anonymous referee for the valuable notes and recommendations.

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РЕШЕЊА ЗА КРИВУ СЈАЈА И ВАРИЈАБИЛНОСТ ВАН ЕКЛИСПЕ ЗА KIC 10031409, KIC 11228612, KIC 11403216 И KIC 11913071

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УДК 524.386
Оригинални научни рад

Извели смо решења за криву сјаја код четири детектоване одвојене двојне звезде посматране у мисији *Kepler*. Као резултат одредили смо њихове орбиталне инклинације, температуре и релативне звездане радијусе. KIC 10031409 и KIC 11228612 показују делимичне еклипсе, док компоненте KIC 11403216 и KIC 11913071 пролазе кроз фазу тоталних еклипси. Секундарна компоненета код KIC 11403216 је вероватно M патуљак касне спектралне поткласе или браон патуљак. Варијације које се дешавају ван еклипсе код KIC 10031409, KIC 11228612 и KIC 11913071 мењају се са орбиталним периодом и могле би се објаснити пегама на синхроно ротирајућој звезди(ма). Варијација ван еклипсе код KIC 11403216 се дешава са трећином њеног орбиталног периода и могући узрок је асинхроно ротирајућа компонента. Резонанца у износу 1:3 код KIC 11403216 захтева даље истраживање.