The Bulgarian Contribution to the Study of variable stars on observational data from the *Kepler* mission

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Abstract. This review paper presents the results of investigations of variable stars obtained by Bulgarian astronomers based on observations of *Kepler* mission. The main contributions are: determination of orbits and global parameters of more than 100 binary stars; creation of the largest catalog of eccentric stars; identification of sixty new binaries with eccentricity over 0.5; discovery of 19 heartbeat stars; detailed investigation of the spot and flare activity of several binary stars; asteroseismic study of three pulsating stars; detection of deep transits of WD 1145+017 due to its disentangling planet system. The paper illustrates not only scientific significance but also educational and social impact of the work on these tasks.

Key words: binaries: close – binaries: eclipsing – methods: data analysis – stars: fundamental parameters – stars: pulsating – stars

Introduction

The *Kepler* mission (Borucki et al. 2010) is one of the most spectacular astronomical projects of NASA, whose main task was to search for Earth-like exoplanets in the habitable zone of exoplanets around sun-like stars. The *Kepler* 0.95 m telescope was launched in March 2009. Its field of view of 105 square degrees (i.e. 0.25 % of the sky) was located in the constellations Cygni and Lyrae. The detector consists of 42 CCD cameras. *Kepler* observed stars in the range 7–17 mag in the spectral range 428–893 nm with accuracy about 0.0001 mag.

During the first stage of the mission, *Kepler* discovered several thousand planetary candidates, over 1000 of which have already been confirmed. In addition, a huge database was created for different types of variable stars: pulsating, eruptive, binary stars. The huge precision and continuity of *Kepler* observations allowed detection of third-order effects such a relativistic beaming (Bloemen et al. 2011) as well as tidally excited oscillations (harmonics of the orbital period) and brightening around the periastron (theoretically predicted by Kumar et al. 1995). The newly-discovered objects were called "heartbeat" (HB) stars due to the shape of their light curves reminiscent an echocardiogram (Thompson et al. 2012).

In 2011 part of the *Kepler* observations (quarters Q0, Q1, and Q2) became available to the astronomical community. This unique database was used for valuable investigations. Answering the appeal to use the available resources of the *Kepler* database for additional research Bulgarian astronomers undertook a study of some types of variable stars.

1 Chronology of Bulgarian participation

The Bulgarian participation in the research of objects observed by *Kepler* started in 2011 when in the framework of the educational project *MyKepler* (Fig. 1) pupils from Varna were trained and began to work on the processing of *Kepler* data, searched light variability and tried to classify the variability (Fig. 2). Further, they prepared 12 reports and presented them on National Astronomical Scholar Conferences in 2012–2013. The paper of Radeva, Kyurkchieva & Dimitrov (2014) summarized the results of these educational tasks based on *Kepler* data.

Fig. 1. Site of the project *MyKepler*

Our first article on modeling of *Kepler* data (Dimitrov, Kjurkchieva & Radeva 2012) contained a study of 19 binary stars, most of them with eccentric orbits, and an exoplanet candidate (Fig. 3).

Almost twenty publications appeared in the next years. They contain not only the modeling of *Kepler* data for dozens of binary stars, but also analysis of their out-of-eclipse light curves leading to discoveries of effects of cool spots, differential rotation and activity cycles as well as flares. For a significant part of the targets tidal-induced features at the periastron were detected and they were classified as heartbeat stars. Moreover, observations and asteroseismic analysis of three *Kepler* pulsating stars were carried out.

2 Scientific results

Further we summarize the main results of the Bulgarian participation in the study of variable stars based on observational data from the *Kepler* mission.

(1) Formulae for preliminary calculation of the eccentricity e_0 and periastron angle ω_0 of eccentric orbits were derived (Kjurkchieva & Vasileva 2015)

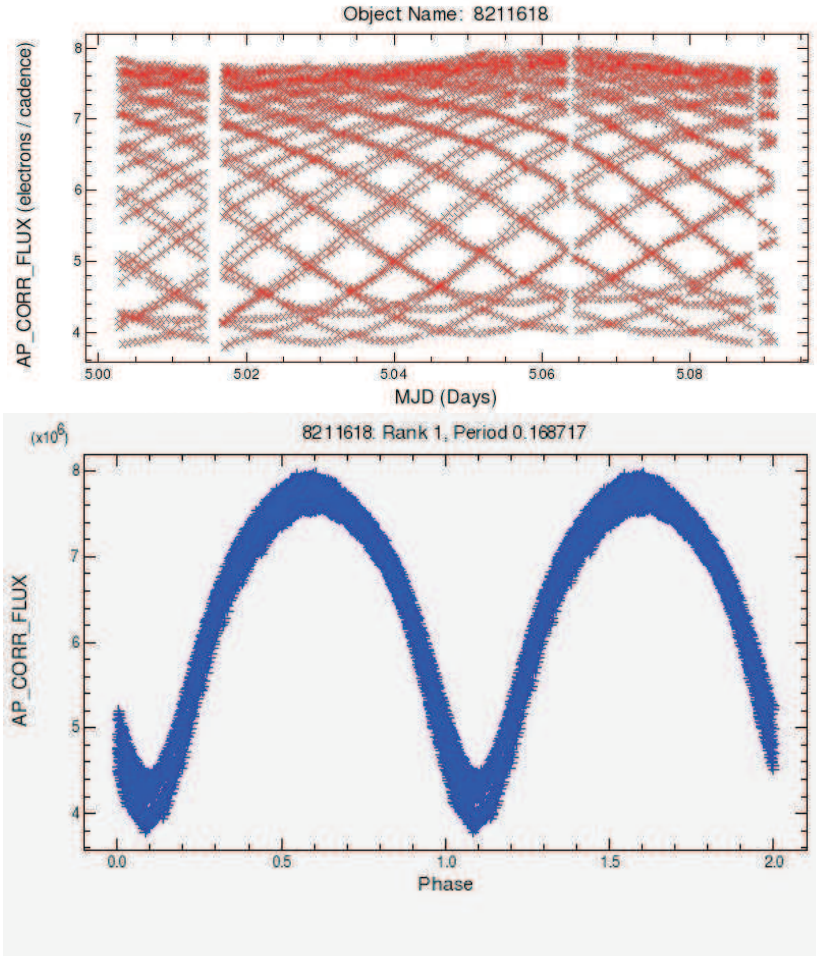

Fig. 2. Result of reducing of data of KIC 8211618, from Radeva, Kyurkchieva & Dimitrov (2014)

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

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

where $w_{1.2}$ are widths of the eclipses (in phase units) while φ_1 and φ_2 are their phases.

(2) Spectral observations of 7 *Kepler* heartbeat stars with highly eccentric orbits were carried out. Global and orbital parameters of these binaries

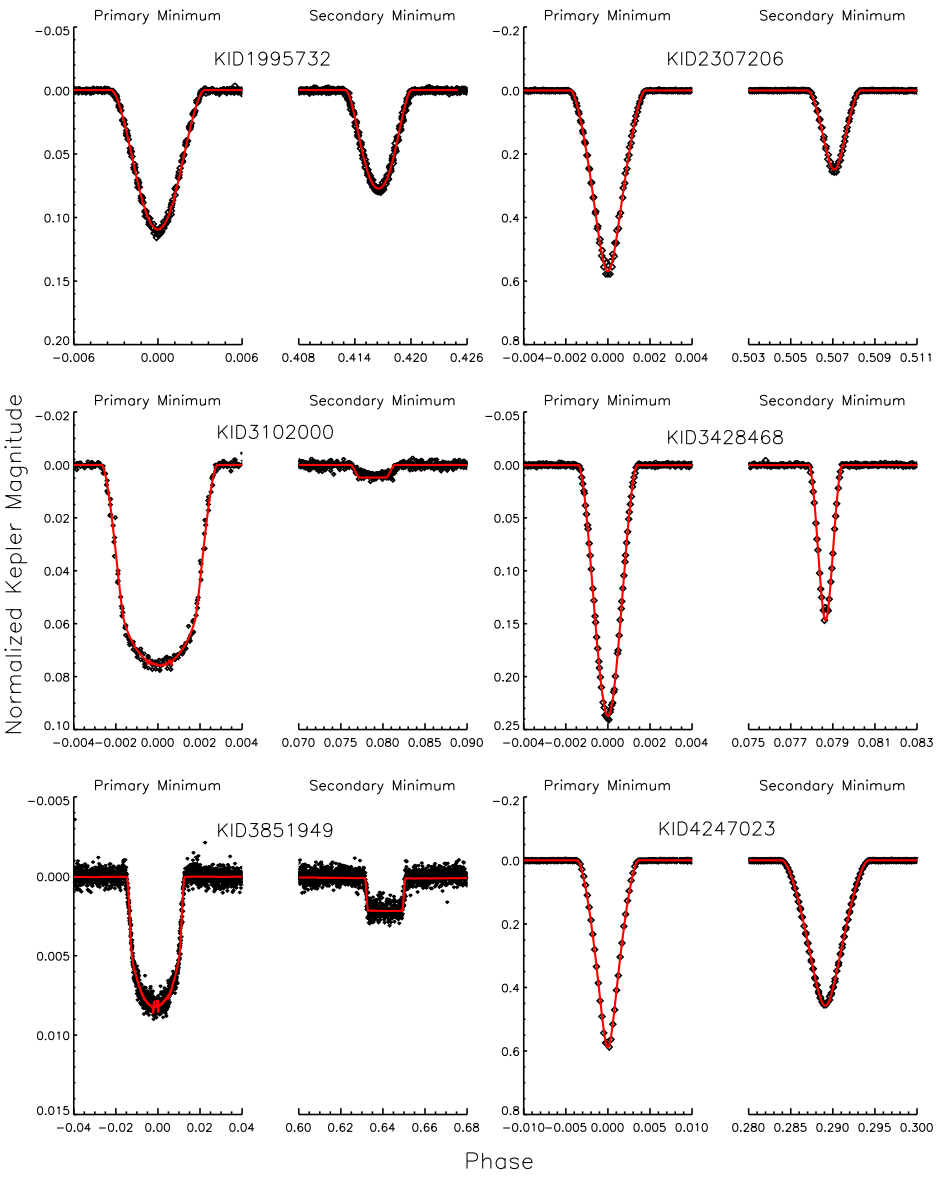

Fig. 3. Observational and synthetic light curves of eclipsing binaries on eccentric orbits, from Dimitrov, Kjurkchieva & Radeva (2012)

were determined by simultaneous solutions of their radial velocity curves and *Kepler* light curves (Fig. 4, Dimitrov, Kjurkchieva & Iliev 2017).

(3) The *Kepler* light curves of 47 eclipsing binary stars with circular orbits were modelled and the global parameters of their components were

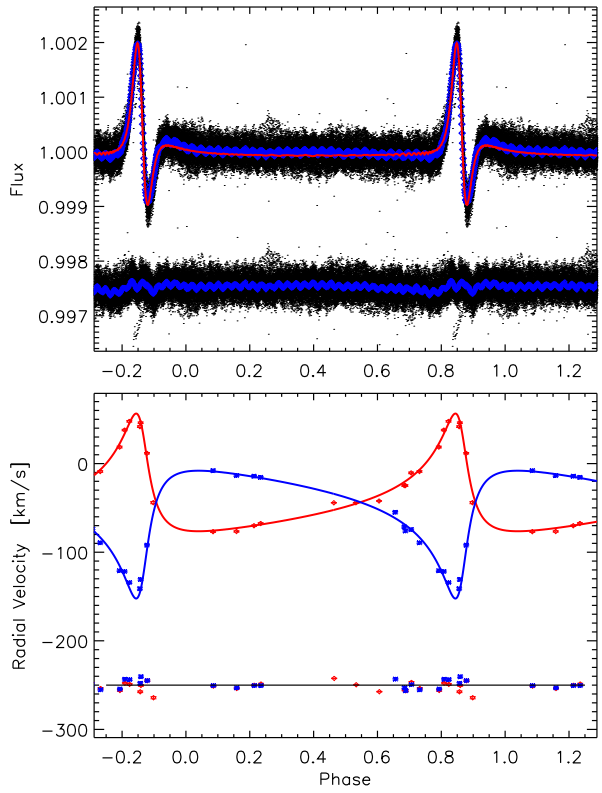

Fig. 4. Model of the *Kepler* light curve and our radial velocity curves of KIC 03547874, from Dimitrov, Kjurkchieva & Iliev (2017)

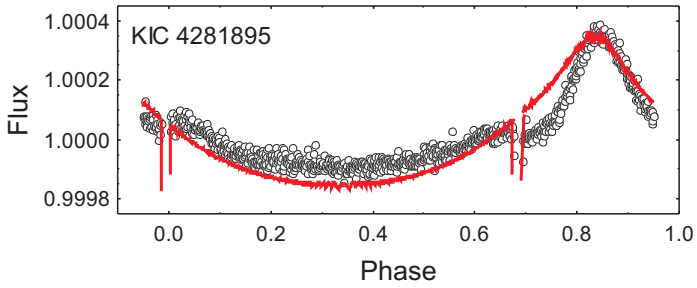

Fig. 5. Tidally-induced feature at the periastron and its fit, from Kjurkchieva & Vasileva (2015)

determined (Kjurkchieva & Atanasova 2016, 2017; Kjurkchieva, Atanasova & Dimitrov 2016; Kjurkchieva & Dimitrov 2016).

(4) The *Kepler* light curves of 62 eclipsing binary stars with eccen-

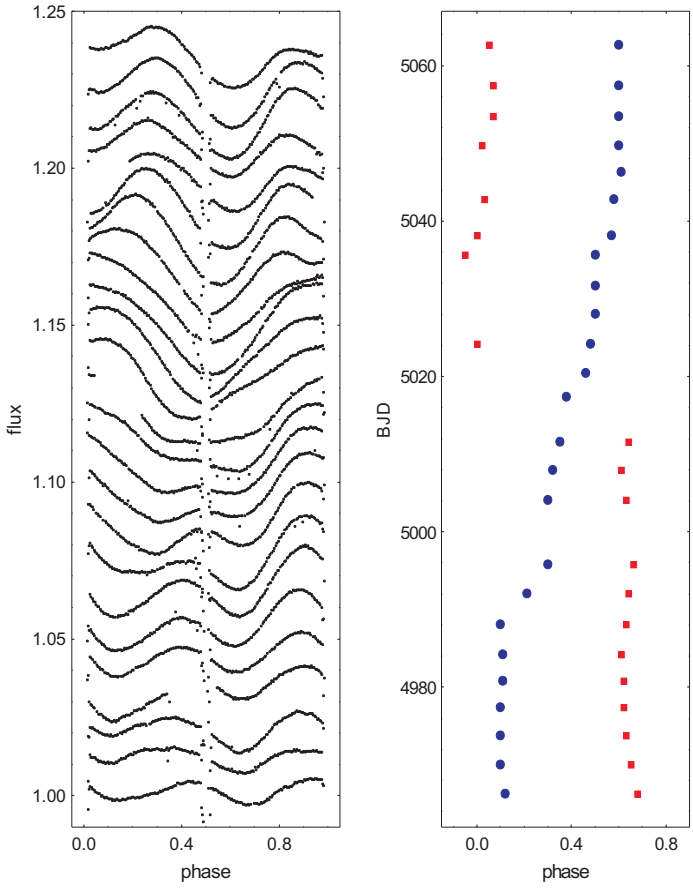

Fig. 6. Left panel: Out-of-eclipse variability of KIC 5802470 throughout 25 consecutive orbital cycles (phased by the orbital period); Right panel: The changes of the phases of the maximum visibility of the cool spots throughout the same period of time which remind the flip-flop effect (from Kjurkchieva, Atanasova & Dimitrov 2016)

tric orbits were modelled and the global parameters of their components were determined (Kjurkchieva & Vasileva 2018; Kjurkchieva, Vasileva & Dimitrov 2016a, b; Kjurkchieva & Vasileva 2016, Kjurkchieva & Vasileva 2015a, b; Dimitrov, Kjurkchieva & Radeva 2012).

(5) We determined the orbital elements of 530 stars with eccentric orbits and thus created the largest catalog of eccentric stars (Kjurkchieva, Vasileva & Atanasova 2017). Sixty new binaries with eccentricity over 0.5 were found (Kjurkchieva, Vasileva & Atanasova 2017).

(6) Tidally-induced effects at the periastron of 12 *Kepler* stars were detected and they were classified as HB objects (Fig. 5).

(7) We detected out-of-eclipse variability due to cool spots on stellar

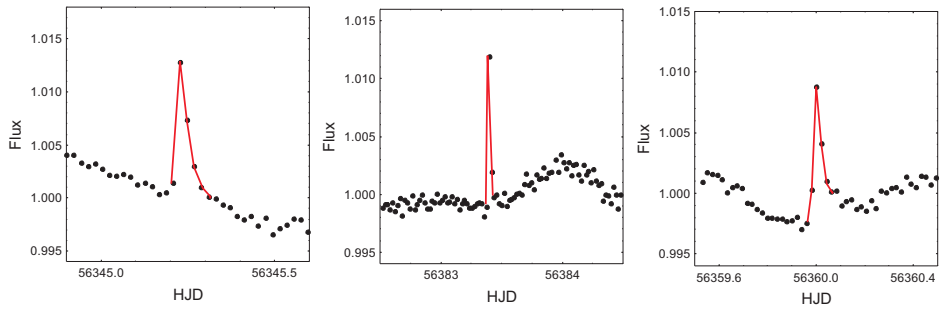

Fig. 7. Observed flares of KIC 7691527, from Kjurkchieva, Vasileva & Dimitrov (2016)

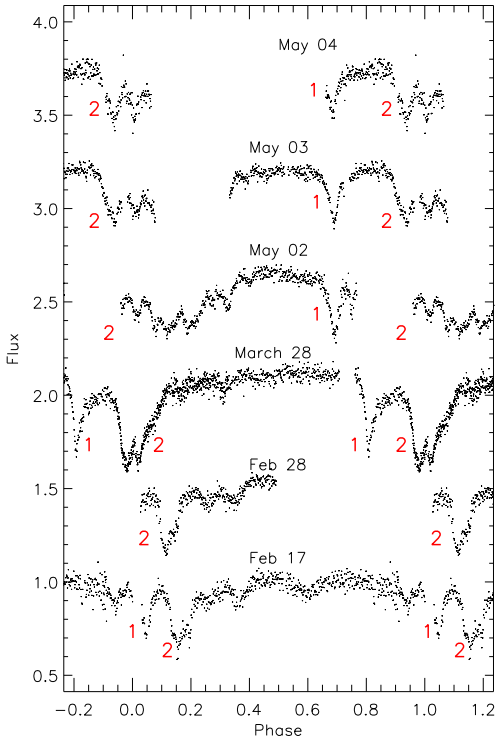

Fig. 8. Repeated transit structures of WD 1145 + 017, from Kjurkchieva, Dimitrov & Petrov (2017)

components for 9 stars (Fig. 6) as well as flares of some binary stars (Fig. 7).

(8) Our photometric observations of the white dwarf WD 1145+017 (Fig. 8) in 2017 (Kjurkchieva, Dimitrov & Petrov 2017) revealed deep tran-

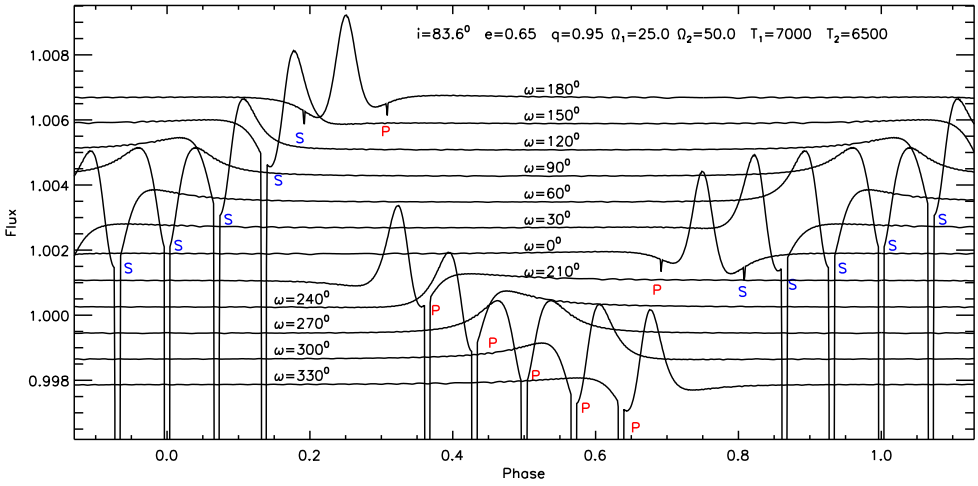

Fig. 9. Dependence of the shape and amplitude of the tidal-induced signal on the periastron angle, from Dimitrov, Kjurkchieva & Iliev (2017)

sits of structures belonging to a thin non-homogeneous disk, possibly a residue of a planetary system.

(9) We investigated the dependence of the shape and amplitude of the tidally-induced signal at the periastron on the orbital and global parameters of the eccentric binaries (Figs. 9–10) (Dimitrov, Kjurkchieva & Iliev 2017).

(10) We built the eccentricity-period diagram (Fig. 11) for all known eccentric binaries (Kjurkchieva, Vasileva & Atanasova 2017).

(11) Bulgarian astronomers participated in a multi-site photometric campaign on two *Kepler* targets, KIC 9408694 (V2367 Cyg) and KIC 6382916, in order to determine their pulsation modes. Moreover, they carried out high-resolution spectral observations to estimate the stellar parameters and projected rotational velocity of these objects (Ulusoy et al. 2013a, b).

(12) The asteroseismic study of KIC 6462033 (Ulusoy et al. 2014) exhibited three modes with frequencies 0.92527, 2.03656 and 1.42972 d^{-1} as well as more than a few hundreds of combination terms. The results confirmed that KIC 6462033 pulsates in the frequency range of γ Dor-type variables. The observed lines Hβ and Hα were modelled by $T_{\rm eff}$ = 7150 K, around 1200 K lower than that given by the KIC catalogue.

The social impact of all these scientific results is exhibited by the appearance of the name D. Kjurkchieva, the leading author of the most of the foregoing investigations, in the site of the *Kepler* mission, section Most active authors (https://keplerscience.arc.nasa.gov/publications.htmlmost-active-authors) (Fig. 12). This fact is indicative of the high impact of the bulgarian astronomers.

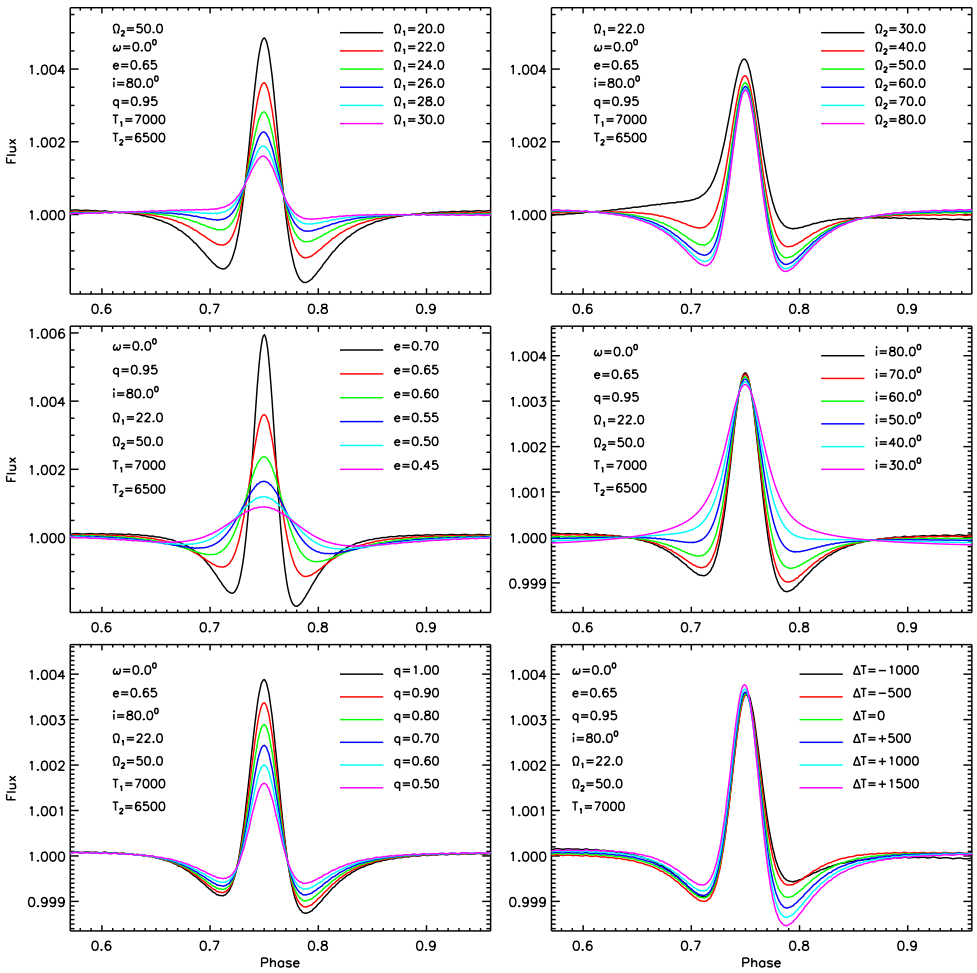

Fig. 10. Dependence of the shape and amplitude of the tidal-induced signal on the orbital and global parameters, from Dimitrov, Kjurkchieva & Iliev 2017

Conclusions

The Bulgarian contribution in the investigations of *Kepler* data contains a study of more than six hundred variable stars of different types. The main results are: determination of orbits and global parameters of more than 100 binary stars; creation of the largest catalog of eccentric stars; identification of sixty new binaries with eccentricity over 0.5; discovery of 19 heartbeat stars; detailed investigation of the spot and flare activity of several binary stars; asteroseismic study of three pulsating stars; detection of deep transits of WD 1145+017 due to its disentangling planet system.

Besides, the Bulgarian participation in the study of variable stars based

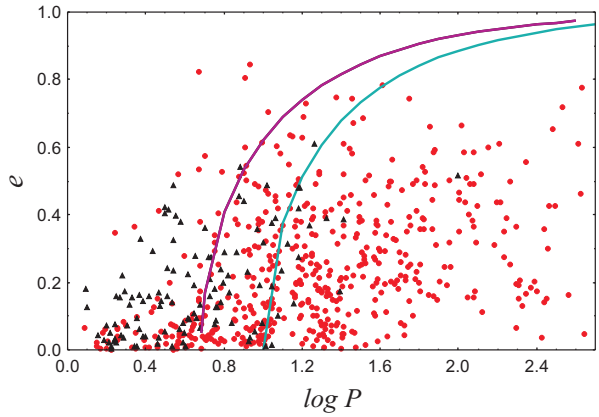

Fig. 11. Relation period-eccentricity, from Kjurkchieva, Vasileva & Atanasova 2017

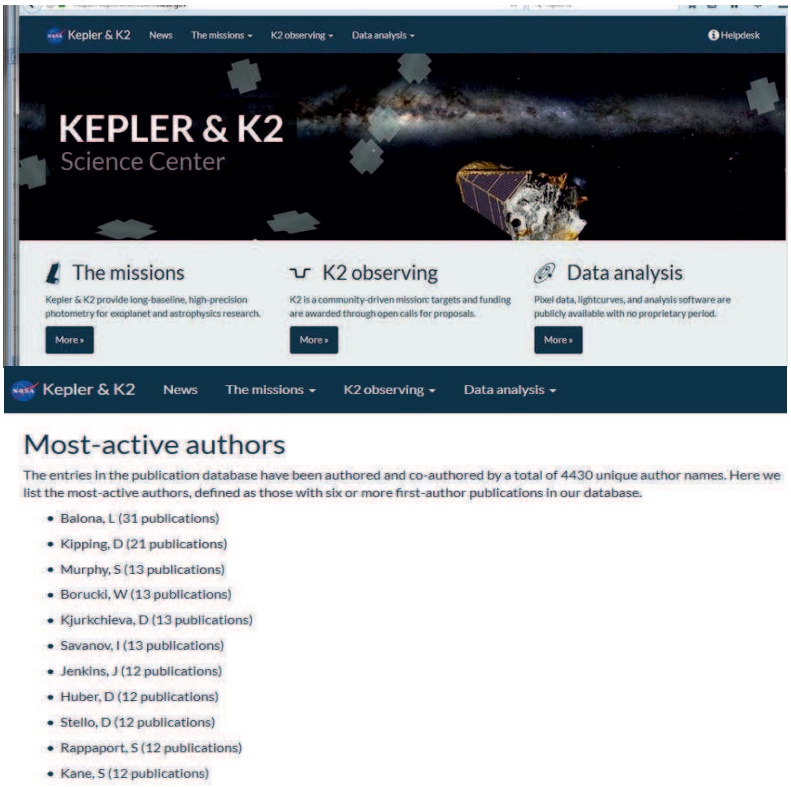

Fig. 12. *Kepler* site and list of the most active authors (September 2017)

on observational data from the *Kepler* mission had not only scientific, but also educational and social impact.

Acknowledgments

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