Investigation of dynamical phenomena with space telescopes in pulsating variable stars
NKFIH K-115709
1 September 2015 – 31 August 2019

Closing report

Introduction

The main aims of this project were the investigation of nonlinear dynamical phenomena in pulsating variable stars: **(1) Cepheids and RR Lyrae stars, (2) main sequence pulsators and (3) pulsating variables in binary systems** with the use of space telescopes (Kepler/K2) and ground-based facilities and to conduct preparatory work for upcoming space photometric missions, like TESS. These space photometric missions provide unprecedented precision and coverage in measuring the brightness variation of stars enabling new types of investigations. Members of the research group played a key role in the Kepler and TESS Asteroseismic Science Consortia by leading the RR Lyrae and Cepheids Working Groups, and by proposing classical pulsating variable stars in both missions. These stars otherwise would not had been observed. The PI was invited to the K2 Users' Panel. We also participated in the work of the classification of variable stars in the TESS Asteroseismic Science Consortium's T'DA (TESS data for Asteroseismology) coordinated action (sub-group).

During the K2 Mission, the sky along the ecliptic was monitored. We contributed to **65 target proposal programs of which 21 was led by our research group members.** Due to the exhaustion of fuel, the spacecraft stopped working in November, 2018. However, launch of TESS has been successful in April 2018, and the mission completed its first year of operation mapping the southern hemisphere, and started the observations of the northern sky in July 2019. We have contributed to and are leading 'first light papers' within the TESS Asteroseismic Science Consortium (roAp, delta Scuti and gamma Dor stars, RR Lyrae, Cepheids).

During the project we published **142** scientific publications, **97** of them are published in refereed, impact factor journals. **Twenty-nine** of them are first-authored, **12** are based on Gaia results. The cumulative impact factor is **480.938**. We published **40** conference papers and **5** other publications (white papers). These publications were cited 6235 times (Gaia-papers 5100 times, and the rest of the papers 1135 times) until the reporting deadline. Self-citations were minimal (230). Calculated **h-index** of the published papers is **20**, i10 index (number of papers with at least 10 citations) is 36, while i100 index (number of papers with at least 100 citations) is 8.

The research plan was executed according to the original plans with minimal changes. The list of the original participants changed slightly, but we always succeeded in replacing those young colleagues who left the Institute. P. Klagyivik left because he got a position at IAC (Canary Islands, Spain) and later in Berlin in DLR. Á. Juhász left in August, 2018, after his first year of PhD studies, but he was immediately replaced by A. Forró, who started her PhD in September, the same year. Four undergrad students were also supported by the project. As usual, the scope of the research was a bit broadened to touch eclipsing binaries, exoplanets, Solar System studies, all covered by space photometry. This resulted in a wider collaboration network (both domestic and international), with a positive impact on the scientific results of the team.

Scientific results

RR Lyrae stars

The Kepler spacecraft during its nominal mission and later in the K2 mission observed many RR Lyrae stars suggested by our research group. The uninterrupted, very high precision observations allowed the investigation of several dynamical phenomena (modulation, nonradial modes, period doubling, resonances, etc.) for the first time. Our group is world-leading in this area. Only the most important results are mentioned here. All published Kepler and K2 RR Lyrae light curves are publicly available at the website of our research group[1]. To complement these investigations, the photometry from large sky surveys (ASAS, OGLE) was also used for detailed RR Lyrae investigations.

We presented our photometric solutions using extended apertures in order to conserve the flux of the stars to the highest possible extent for **RR Lyrae stars observed in the K2 mission**. With this method we are able to avoid most of the problems that RR Lyrae light curves produced by other pipelines suffer from. We made publicly available the EAP (Extended Aperture Photometry) of 432 RR Lyrae stars observed in campaigns 3, 4, 5, and 6 at our website. We made steps to automatize the application of our method, and the homogeneous EAP treatment of all the other campaigns is in progress. We investigated the presence of the Blazhko effect in the stars, and found it to be 44.7% among the RRab stars, in agreement with results from independent samples. We also identified four anomalous Cepheid candidates in the sample one of which is potentially the first Blazhko-modulated member of its class (Plachy et al. 2019).

We presented the **first observations of extragalactic pulsating stars in the K2 ecliptic survey**. Variability of all three known RR Lyrae stars in the dwarf spheroidal galaxy Leo IV were successfully detected, at a brightness of Kp~21.5 mag. We identified one modulated star and another likely Blazhko candidate with periods of 30 days and more than 80 days, respectively. EPIC 210282473 represents the first star beyond the Magellanic Clouds for which the Blazhko period and cycle-to-cycle variations in the modulation were unambiguously measured. The photometric [Fe/H] indices of the stars agree with earlier results that Leo IV is a very metal-poor galaxy. The image subtraction method we used will be useful for future space photometric missions to reliably extract photometry from faint confused sources (Molnár et al. 2015).

We analyzed **non-Blazhko RRab stars in the Kepler sample**. We found that all stars which are brighter than a certain magnitude limit show significant cycle-to-cycle light-curve variations. This is a completely new and unexpected result. We also found permanently excited additional modes for at least one-third of the sample. Other stars show temporarily excited additional modes. The presence of the Blazhko effect was carefully checked and we identified one new Blazhko candidate, but for at least 16 stars the effect can be excluded. Thus, the cycle-to-cycle variation phenomenon is independent of the Blazhko effect and the Blazhko incidence ratio (51-55%) agrees with previous studies, and excludes a very high (>90%) incidence rate with very high confidence (Benkő et al. 2019).

We explored a **new mathematical formalism to describe Blazhko RR Lyrae light curves**. Almost periodic functions describe well light curves that are modulated and predict an observable shift of the

[1] https://konkoly.hu/KIK/data_en.html

Fourier harmonics of the main pulsation frequency from the exact harmonic position. This phenomenon was observed in two Kepler Blazhko RRab stars. The effect is detectable only if the phase variation part of the Blazhko effect is of large amplitude and non-periodic enough, additionally, the time span of the observed light curve is sufficiently long. These conditions explain why this effect has not been discovered before (Benkő, 2017).

We investigated 1234 fundamental mode RR Lyrae stars observed by the All Sky Automated Survey (ASAS) to investigate the Blazhko effect. We identified 87 Blazhko stars and 22 stars showing long-term period variations. The distribution of modulation periods of the newly identified Blazhko stars corresponds well to the distribution of modulation periods of stars located in the Galactic field, Galactic bulge, Large Magellanic Cloud, and globular cluster M5 (Skarka et al. 2016). We studied the **incidence rate of the Blazhko effect in RRab stars** in the Galactic bulge. The number of identified Blazhko stars is 3341, which is the largest sample ever studied. We found that at least 40% of the stars show modulation. Blazhko stars with extremely long periods were also identified. No correlation was found between the occurrence of the Blazhko-modulation and photometric metallicities, intrinsic colors and absolute magnitudes (Prudil & Skarka, 2017).

We discovered a new form of double-periodic pulsation in RRL stars. In four long-period (P > 0.6 d) RRab stars observed by OGLE, we detected additional, low-amplitude variability. The period ratios fall in a range of ordinary double-mode RRL stars, with the exception of one object. The observed period ratios can be well modelled with high-metallicity pulsation models. Five other candidates share the same characteristics (Smolec et al. 2016). Another group **of RRab stars with additional periodicities was also discovered** in the OGLE Galactic bulge photometry. Here the period ratios are much lower than the canonical RRd period ratio. The amplitudes of the extra periodicities are also lower than for regular RRd stars. Some of these stars show the sign of Blazhko-modulation. It is not clear whether radial or non-radial pulsational modes can be invoked to explain these oddballs (Prudil et al. 2017).

Cepheids

We analyzed space photometric observations of several Classical Cepheids (CC), anomalous Cepheids (ACs), and Type II Cepheids (T2C) including W Vir, BL Her and RV Tau type variable stars with Kepler/K2 and MOST. OGLE and Gaia observations also helped to achieve several 'firsts' in this field.

We revisited the 4-year-long continuous **Kepler observations of the bright CC, V1154 Cygni**, the only one in the original Kepler field. We identified modulation of the main pulsation frequency with a period of ~159 d. We detected another modulation with a period of about 1160 d. The star shows significant power in the low-frequency region that we identified as **granulation noise** for the first time in any CC. We obtained new radial velocity observations which suggest that V1154 Cygni has no high mass star companion (Derekas et al. 2017).

We investigated **V473 Lyrae**, a second-overtone, strongly modulated Cepheid with the **MOST space telescope.** We **discovered period doubling, being the first case** in any CCs. Simultaneous ground-based photometry and spectroscopy provided the phase lag parameter (the phase difference between maxima in luminosity and radial velocity, a good pulsation mode diagnostics) of a second-overtone Cepheid for the first time. Period doubling provides a strong argument that mode interactions occur in some CCs and we may hypothesize that it could explain the amplitude modulation, as recently proposed for Blazhko RRL stars (Molnár et al. 2017).

We presented the **first analysis of W Vir stars observed by the K2 mission**. Cycle-to-cycle variations were detected in the light curves of KT Sco and the globular cluster member M80-V1. While the variations in the former star seemed to be irregular on the short time-scale of the K2 data, the latter appears to experience period doubling in its pulsation. Ground-based color data confirmed that both stars are W Vir-type pulsators, while historical photometric time series data revealed drastic period changes in both stars. These results support the notion that non-linear dynamics plays an important role in the pulsation of W Virginis-type stars (Plachy et al. 2017).

We analyzed the photometry of the largest sample of T2Cs so far: 924 stars observed by OGLE in the Galactic Bulge. We discovered the first examples of double-mode BL Her-type stars. Period doubling was also detected in three BL Her-type stars. Through identification of numerous period-doubled W Vir stars we showed that the appearance of the period doubling effect, and hence the transition towards RV Tau class, is a smooth process that starts at pulsation periods slightly above 15 days. Interchange of the deep and shallow pulsation cycles was identified in tens of RV Tau variables. One RV Tau star is a strong candidate for period-4 pulsation. Quasi-periodic modulation of pulsation in all sub-classes of T2Cs was also reported for the first time. Irregular changes of pulsation amplitude and period on various time-scales were found to be common in all subgroups of T2Cs. These various dynamical phenomena are crucial to better understand the physics of this class of distance indicators (Smolec et al. 2018).

We also studied the period-luminosity (PL) and period-radius relations of a large sample of **T2Cs and ACs in the Small and Large Magellanic Clouds** detected in OGLE-III data. We derived the period-luminosity-mass-temperature-metallicity relations and estimated the pulsation mass. These relations are useful to measure cosmic distances, and are complementary to the best studied CCs and RR Lyrae PL relations. In addition, a subsample of targets was investigated for possible binarity by looking for the light-time travel effect, out of which 20 systems may be new binaries (Groenewegen & Jurković 2017). We presented the **first period-luminosity and period-radius relation of Galactic RV Tauri variable stars** using literature and Gaia data. The period-luminosity relation of galactic RV Tauri stars is steeper than that of the shorter-period T2Cs, in agreement with previous result obtained for the Magellanic Clouds and globular clusters. The median masses of RVa and RVb stars were calculated to be 0.45-0.52 and 0.83 solar masses, respectively (Bódi & Kiss, 2019).

We analyzed the light variations of **the RVb-type DF Cygni** based on continuous, **4-year-long Kepler photometry** and almost half a century of visual data from the AAVSO database. DF Cygni shows a rich behavior on all timescales. There is a remarkably coherent slow variation, whereas the 50-d period pulsation shows alternating minima, characteristic of the RV Tau class. Both types of light variation fluctuate in time, with a constantly changing interplay of amplitude and phase modulations (Bódi et al. 2016). RV Tau light variability is supposed to be governed by chaotic dynamics. However, observational evidence for chaos is usually hard to come by. We searched for the signs of chaos in DF Cygni. We used the Global Flow Reconstruction method to estimate the quantitative properties of the dynamics driving the pulsations of the star. Our analysis revealed that the pulsation of DF Cyg could be described as a chaotic signal with a Lyapunov dimension of ~2.8. DF Cyg is only the third RV Tau star, and the first of the RVb subtype, where there is indication for the **presence of low-dimensional chaos** (Plachy et al. 2018).

Theories assumed binarity and circumstellar dust to explain the **long-term modulation** of the mean brightness of **the RVb subclass**. We investigated whether the amplitude modulations are consistent with the dust obscuration model. We compiled long-term photometric data for RVb-type stars, including visual observations, ground-based CCD photometry, and ultra-precise space photometry from the Kepler space telescope. We converted all available observations to flux units, and found a surprisingly uniform correlation between the pulsation amplitude and the mean flux: they scale linearly with each other for a wide range of fluxes and amplitudes. This means that the pulsation amplitude remains constant when measured relative to the system flux level. Thus, we demonstrated that when fluxes are used instead of magnitudes, the amplitude attenuation is naturally explained by **periodic obscuration** from a large opaque screen, most likely corresponding to a **circumbinary dusty disk that surrounds the whole system** (Kiss & Bódi, 2017).

Hybrid main-sequence pulsators

We used the time-delay method to identify **binarity in hybrid γ Dor (g-mode) – δ Sct (p-mode) pulsators** among the more than 1700 hybrid candidates in the Kepler sample. In addition, an extensive spectroscopic campaign was conducted by our team in the Piszkés-tető Observatory to investigate the rotational properties of the hybrid candidates. The photometric properties (light curve analysis, frequency and period spacings) were investigated in order to better understand the nature of these intriguing objects and establish their true occurrence rate in the Galaxy. Based on the time-delay method and spectroscopic observations a significant fraction (27%) was found to be in binary systems (Lampens et al. 2018). We also searched for companions around hybrid γ Dor/δ Sct stars with the **frequency modulation method** using Kepler data. Our best candidate is KIC 5709664, where we could identify Fourier peaks with sidelobes, suggesting binary orbital motion. With the phase modulation method and spectroscopic measurements, we determined that the pulsator is a hybrid γ Dor/δ Sct star in an eccentric binary system with an orbital period of ~95 d and an eccentricity of 0.55. The measured mass ratio is 0.67. We analyzed the pulsation content and extracted 38 frequencies with amplitudes larger than 20 μmag. We inferred rotation periods of 0.56 and 2.53 d for the primary and secondary, respectively (Derekas et al. 2019).

Binaries

RR Lyrae stars often show **cyclic period changes**. We investigated two such stars. **KIC 2831097** is our discovery, a new RRc binary candidate in the original Kepler field. The systematic phase variations – if interpreted as light travel time effect – might be caused by orbital motion in a binary system with a possible black hole companion. The assumed eccentric orbit with the period of 2 years is the shortest among the non-eclipsing RRL binary candidates (Sódor et al. 2017). However, the long-term cyclic variations of the pulsation period of **Z CVn** are likely intrinsic to the star based on our investigations. If the binary hypothesis is valid, Z CVn orbits around a black hole with minimal mass of 56 solar masses on a very wide and eccentric orbit. There is, however no observational evidence of the black hole in the direction to Z CVn. The main objection against the binary hypothesis is the comparison of the systemic radial velocity curve model and spectroscopic observations that clearly shows that Z CVn cannot be bound in such a binary (Skarka et al. 2018).

We studied the eclipse timing variation of short period eclipsing binaries monitored during the OGLE-IV survey. From the 425193 EBs we identified 992 potential hierarchical triple (or multiple) system candidates exhibiting light-travel-time effect. We obtained the orbital parameters of these systems and carried out statistical analyses on the properties of these candidates. We found that there is a significant lack of triple systems where the outer period is less than 500 days. There are four candidates that show double periodic eclipse timing variations, which indicates the presence of a fourth companion. For one system, the third component is found to be probably in the substellar mass domain (Hajdu et al. 2019). In addition, we participated in the compilation of the seventh catalog of the Kepler eclipsing binary catalog (Kirk et al. 2016), and contributed to the discovery of a unique quintuple star system containing two eclipsing binaries (Rappaport et al. 2016).

Other topics

Members of our research group work in the Gaia Data Processing and Analysis Consortium, Coordination Unit 7 (Variability processing). They worked on the data processing and first scientific results based on **Gaia Data Release 2 (DR2).** They were part of several Gaia instrument papers on the survey properties, variability processing, open clusters, testing the parallaxes of Cepheids and RR Lyrae stars, variable stars in the colour – absolute magnitude diagram, kinematics of globular clusters and dwarf galaxies around the Milky Way, Milky Way disk kinematics, and Solar System objects. Besides these many-author papers we led projects on **exploiting Gaia – Kepler/K2 synergies.** We used Gaia DR2 to find additional RR Lyrae stars in Kepler and K2 fields. For example, we found four times more RR Lyrae stars in Kepler's original field of view, than were known previously. In addition, Gaia DR2 is an excellent source to validate classification of K2 variables, since many of the K2 targets were assigned with an uncertain variable type classification. Our results show that RR Lyrae parallaxes can be used down to the 15^{th} magnitude, which corresponds to 0,1 milliarcseconds. This means that all RR Lyrae stars observed by TESS will have good parallaxes. An additional benefit of the parallax is the ability to identify blends with background objects (Molnár et al. 2018).

Most aspects of stellar evolution proceed far too slowly to be directly observable in a single star on human timescales. The thermally pulsing asymptotic giant branch is one exception. The combination of state-of-the-art modelling techniques with data assimilated from observations collected by amateur astronomers over many decades provide, for the first time, the opportunity to identify a star occupying precisely this evolutionary stage. We showed that the rapid pulsation period change, and associated reduction in radius in **T UMi** are caused by the recent **onset of a thermal pulse.** We demonstrate that T UMi transitioned into a double-mode pulsation state, and we exploit its asteroseismic features to constrain its fundamental stellar parameters. We used evolutionary models from MESA and linear pulsation models from GYRE to track simultaneously the structural and oscillatory evolution of models with varying mass. We found an initial mass of $2.0\pm0.15M_{\odot}$ and an age of 1.17 ± 0.21 Gyr for T UMi. This is the **most precise mass and age determination for a single asymptotic giant branch star ever obtained.** The ultimate test of our models will be the continued observation of its evolution in real time: we predict that the pulsation periods in T UMi will continue shortening for a few decades before they rebound and begin to lengthen again, as the star expands in radius (Molnár et al. 2019).

We performed ground-based observations at Piszkés-tető Mountain Station to find **new white dwarf** pulsators to be observed later by the **TESS space mission**. We identified four new DA (ZZ Ceti) pulsators, and derived detection limits for the rest of our targets. The new objects will be observed by TESS and will be analyzed by our group (Bognár et al. 2018, 2019a). We also performed asteroseismic investigations on three cool ZZ Ceti type pulsating white dwarfs (HS 0733+4119, GD 154, and Ross 808) and identified new pulsation modes and studied the temporal behavior of many modes on decades-long timescales. All three targets are in that regime of the ZZ Ceti instability strip where short-term amplitude variations or even outbursts are likely to occur, which are not well-understood theoretically (Bognár et al. 2019b).

Other results of the project

Our team is **a well-known research group world-wide in pulsating star research**, signaled by the number of (invited) conference talks, conference Scientific Organizing Committee memberships, three PhD and two DSc degrees obtained, large number of grants and prizes awarded of research group members, as well as membership of the Kepler/K2 and TESS Asteroseismic Science Consortium Steering Committee memberships (R. Szabó) and various international working group leaderships (R. Szabó, L. Kiss, E. Plachy). The European Space Agency PLATO mission Board membership, and ARIEL co-Investigator status of R. Szabó are also worth mentioning. We organized the RRL2015 conference in Visegrád, Hungary, as a pioneering undertaking. However, it proved to be so successful that it is now transformed into a prestigious **conference series** with increasing participant number (RRL2017 in Niepolomice, Poland, RRL2019 in New Mexico, USA), an achievement we are very proud of.

Members of our research group gave **26 conference talks** (including **6 invited**), and **45 poster presentations** at various relevant conferences. The invited talks were: E. Plachy, 2nd BRITE Science Conference, Innsbruck, Austria, Aug, 2016 (*Cepheid investigations in the era of space photometric missions*) E. Plachy, TASC3/KASC10 conference in Birmingham Jul, 2017 (*Cepheid and RR Lyrae studies with TESS: what could 27 days give us),* Z. Kolláth, RRL2017 conference Niepolomice, Poland, Sep, 2017 *(Modeling and/or understanding the Blazhko effect)*, L. Szabados, Observing techniques, instrumentation and science for metre-class telescopes II conference, Tatranská Lomnica, Slovakia, Sep, 2018 (*Selected new results on pulsating variable stars*), Z. Kolláth, PHOST: What physics can we learn from oscillating stars? Conference, Sep 2018 Banyuls-sur-mer, France (*RR Lyrae and Blazhko effect)*, Gy. M. Szabó, PLATO Workshop, Warwick, Sep 2019 (*The Drake-equation of exomoons).*

Dissemination and public outreach were a major focus point during the project. We wrote more than **50 popular papers** (printed or online)[2] mostly on space photometric missions, and delivered **250 translations** to the European Southern Observatory science news[3]. Our members gave **45 popular scientific talks**, to a broad range of audience, from professionals to amateur astronomers, from primary schools to universities and retired people.

The following **prizes** and **grants** were awarded during the reporting period: **Széchenyi-prize** (L. Kiss, 2019), ELTE **Maria Theresia bronze medal** (Gy. M. Szabó, 2018), **Order of Merit of Hungary, Officer's Cross** (L. Szabados, 2017) **Lendület grant** of the Hungarian Academy of Sciences (R. Szabó) *Near-Field cosmology with pulsating stars: a petascale challenge*, **NKFIH Postdoctoral Excellence Program** (E. Plachy, Zs. Bognár), **Postdoctoral National Excellence Program** (E. Plachy), **MTA Junior International Conference Grant** (E. Plachy, A. Derekas, A. Bódi), **Eötvös Fellowship** of the Hungarian State (A. Derekas), **Bolyai Fellowship** (A. Derekas, E. Plachy), **New National Excellence Program Bolyai+** (A. Derekas), **National Excellence Fellowship** (Á. Juhász), **Campus Mundi** (A. Bódi), MTA-ELTE Exoplanet Research Group (Gy. M. Szabó), **DOMUS Hungary scholarship** 5 weeks (M. Jurković), **DOMUS International Conference Grant** (M. Jurković). M. Jurković was a guest researcher in the Royal Observatory of

2 http://www.konkoly.hu/KIK/papers.html
3 http://www.eso.org/public/hungary/?lang

Belgium, Brussels, in 2019 March/April for 1 month hosted by Dr. Martin Groenewegen. L. Kiss became a regular member of the Hungarian Academy of Sciences in 2019.

During the project two **PhD degrees** were awarded (E. Plachy October, 2015, ELTE, M. Jurković, February 2019, University of Belgrade), and one PhD thesis was successfully defended (A. Bódi, September 2019, Szeged University). R. Szabó defended his **DSc thesis** (June, 2017) with a topic strongly aligned with this project (title: *Pulsating variable stars and exoplanet investigations in the era of precision space photometry*). J. Benkő also defended his DSc thesis a year later (June 2018) (title: *Investigation of RR Lyrae variable stars with space telescopes*).

We organized an **international conference** (RRL2015 conference, *High-precision studies of RR Lyrae stars, from dynamical phenomena to mapping the galactic structure*) in Visegrád, Oct 2015, with 60 registered participants. The PI and E. Plachy served as **SOC members** of two conferences: RRL2017 conference, *Revival of the Classical Pulsators: from Galactic Structure to Stellar Interior Diagnostics*, Niepolomice, Poland, Sep 2017, *TESSting Stellar Astrophysics* TASC3/KASC10 Conference, Birmingham, UK, Jul 2017 (R. Szabó, SOC). They are also serving in the SOC of the upcoming RRL2019 international conference, *Frontiers of Classical Pulsators: Theory and Observations*, Cloudcroft, NM, USA in Oct, 2019. The PI was asked to be a SOC member of the TASC6/KASC13 annual TESS/Kepler asteroseismology meeting in Leuven, Belgium in Jul, 2020. E. Plachy was also nominated as a SOC member of the LSST@Europe4 conference to be held in Rome, June, 2020.

Konkoly Observatory became part of the **LSST Consortium** during the reporting period. R. Szabó is a named PI working in four colleagues from his research group in the TVS (Transients and Variable Stars) and SMWLV (Stars, Milky Way & Local Volume) LSST Science Collaborations.