Nonlinear phenomena in Cepheid variable stars

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Final scientific report

Studying pulsation properties of Cepheid variable stars is of great interest, as these stars are key objects in many field of astrophysics, in stellar structure and evolution, in pulsation theory, in galactic and extragalactic distance determination, and they help us to determine the Hubble constant precisely. Cepheids have been long believed to be accurate astrophysical clocks, we had to wait for the era of space photometric missions and large ground-based surveys to realize that this is not the case. The nonlinearity of the Cepheid pulsation is manifesting in different phenomena, such as period doubling, chaos, modulation and other instabilities. Theoretical studies have not yet recovered unambiguously what stands behind these phenomena, the best proposal is the mode interactions hypothesis, but that still need modelling and observational efforts to prove. With the support of NKFIH I contributed to the discovery and characterization of these phenomena in many stars, which can eventually help to explain their origin.

Analysis of space photometric data of Cepheids

Nonlinear phenomena often cause weak signals in the light curves. Fortunately, with the advent of ultra-precise space photometric missions these signals became detectable.

We discovered periodic modulation in the only classical Cepheid star of the primary Kepler mission. The detailed analysis of the 4-year-long continuous observations of V1154 Cygni recovered a 159-day cycle that is present both in the Fourier parameters of the light curve and in the O-C diagram. We also detected a secondary modulation with a period of about 1160 d. Moreover, the star shows significant power in the low-frequency region that we identified as granulation noise. Non-detection of solar-like oscillations indicates that the pulsation inhibits other oscillations. We obtained new radial velocity observations that are in a perfect agreement with earlier data, suggesting that there is no high-mass star companion of V1154 Cygni (Derekas et al. 2017).

V473 Lyr is a strongly modulated second-overtone Cepheid variable star. We detected period doubling in this star, together with the modulation, in the space-based photometry obtained by the MOST satellite. Period doubling was discovered for the first time in a classical Cepheid variable. The co-existence of modulation and period doubling has already been observed in the other important radial pulsator type, the RR Lyrae stars, and it may carry crucial information for the suspected common origin of these two phenomena (Molnár et al. 2017).

After the reaction wheel failures, the Kepler space telescope continued its work along the ecliptic plane in the K2 mission. The observations ended last year leaving an enormous amount of high quality data to process. Thanks to the successful proposals we submitted to the Guest Observer program, dozens of Cepheid and thousands of RR Lyrae candidates were observed. I performed a major part in the target selection of these types and led several K2 proposals myself.

We analyzed two W Virginis-type stars that represent the intermediate period group of Type II Cepheids from data gathered in the early campaigns. We discovered clear cycle-to-cycle variations in the light curves of KT Sco and the globular cluster member star M80-V1. While the variations in the former star seem to be irregular on the short time span of the K2 data, the latter appears to experience period doubling in its pulsation. A comparison with historical photometric time series data revealed drastic period changes in both stars. For comparison, we reexamined ground-based observations of W Vir, the prototype of the class, and concluded that it also shows period doubling instead of mode beating which was earlier proposed (Plachy et al. 2017).

K2 data suffer from strong instrumental issues and the high amplitude variables require special handling that existing photometric pipelines are not designed to provide. We developed a new photometric method called Extended Aperture Photometry, which is optimized for RR Lyrae and Cepheid stars observed by Kepler in the K2 mission. We processed and released more than four hundred RR Lyrae light curves. We investigated, in particular, the presence of the Blazhko effect in the stars and found an occurrence rate of 44.7% among the fundamental-mode RR Lyrae stars, in agreement with results from independent samples. We noticed that the amplitude and phase modulation in the Blazhko stars may behave rather differently, at least over the length of a K2 Campaign. 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).

The detailed investigation of the remaining anomalous and Type-II Cepheids of the K2 mission has not been finished yet, early results have been presented in the TASC4/KASC11 Workshop, as well as the first findings concerning the astroseismology of extragalactic Cepheids, in particular in the IC1613 dwarf galaxy. This latter topic requires careful removal of background systematics and dense stellar field photometry, which still needs more effort.

Systematic search for nonlinear phenomena in ground-based data

Ground-based surveys have the potential to recover nonlinear behavior in Cepheids, however, high data quality and frequent sampling are crucial criteria. The All-Sky Automated Survey (ASAS) database provides long-baseline observations spanning ten years, and a catalog of the variable stars as well. We examined the archived data and detected clear period doubling behavior at three W Virginis-type stars. We discovered that W Vir, the eponym of the group, and SZ Mon both show interchanging events in the order of the deep and shallow minima during the past decades. We also demonstrated that ST Pup, known for its strong period change, exhibited a period doubling episode (Plachy, Kovács & Forgács-Dajka, 2017).

The uncertain variable star classification in the ASAS Survey prevented us from identifying more Cepheid stars with nonlinear behavior and studying them in statistical context. Fortunately, the OGLE IV catalog of bulge Cepheid stars became available at the beginning of 2018. The Optical Gravitational Lensing Experiment (OGLE) Survey is probably the most important ground-based survey to date, its supervised classification system is highly reliable, and the analysis of these carefully handled data already led to several important discoveries in Cepheids and RR Lyrae stars. In a collaboration with Polish colleagues and members of the OGLE Team, we analyzed nearly a thousand Type-II Cepheid stars to detect and investigate various dynamical phenomena, including multimode pulsation, period-doubled pulsation, period-k pulsation, or quasi-periodic modulation of pulsation. Period-doubling

effect was detected in three short-period Type-II Cepheids, or BL Herculis-type stars: two were known previously and one is a new discovery. We identified numerous period-doubled W Virginis stars at periods longer than 15 d, indicating that the transition towards the RV Tauri class (over 20 days), where period doubling is common, is a smooth process. We found one RV Tauri-type star to be a strong candidate for period-4 pulsation, which evolved from the period doubled state via bifurcation. We detected modulation in 16 BL Herculis, 9 W Virginis and 7 RV Tauri stars. We also discovered the first examples of BL Herculis-type stars that exhibit double-mode pulsation. Quasi-periodic modulation of pulsation in all sub-classes of Type-II Cepheids has been reported for the first time. Modulation was detected in 16 BL Her, 9 W Vir and 7 RV Tau stars. Irregular changes of pulsation amplitude and period on various time-scales turned to be common in all sub-groups of type II Cepheids (Smolec et al. 2018).

Nonlinear dynamical analysis

It has already been proposed that the pulsation of RV Tauri-type variables can be governed by chaotic dynamics. However, observational evidence for this happening is usually hard to come by, and it was shown only in two cases. Using the continuous, 4-year-long observations of DF Cyg, the only RV Tauri-type star of the Kepler mission, we found the third star, and the first of the RVb subtype, where the non-linear analysis indicates low-dimensional chaos in the pulsation. We applied the Global Flow Reconstruction method to estimate the quantitative properties of the dynamics driving the pulsations of the star. The secondary, long-term light variation, i.e. the RVb phenomenon, was removed in the analysis with the empirical mode decomposition method. Our analysis revealed that the pulsation of DF Cyg could be described as a chaotic signal with a Lyapunov dimension of ~2.8 (Plachy, Bódi & Kolláth, 2018).

Contributions to the Gaia and TESS missions

The long-awaited second data release of the Gaia mission, DR2, provides many additional pieces on information to the understanding of our galaxy. As an active member of the Gaia Consortium I co-authored three DR2 papers connected to my project.

The aim of the first paper was the identification of variable star candidates, for which the processed Gaia data consist of the G, G_{BP}, and G_{RP} photometry obtained during the first 22 months of operations as well as positions and parallaxes. Various methods from classical statistics, data mining, and time-series analysis were applied and tailored to the specific properties of Gaia data, as were various visualization tools to interpret the data. The DR2 variability catalog contains more than 220 thousand RR Lyrae stars, 11 thousand Cepheids, and numerous other variables, about half of which are newly identified (Holl et al., 2018).

We investigated the purity and completeness of the Gaia classification results using the continuous light curves of the observed targets from the Kepler and K2 missions, focusing specifically on RR Lyrae and Cepheid pulsators. We identified over a thousand RR Lyrae and about 40 Cepheid variables from Gaia DR2 in the targeted observations of the two missions and more than 200 RR Lyrae targets in the full-frame images of the original mission. We conclude that the RR Lyrae catalogue has a completeness between 70-78%, and provide a purity estimate of 92-98%. (Molnár et al., 2018).

The validation process has been an important step in the all-sky classification pipeline of common high-amplitude pulsators. A semi-supervised classification approach was employed, firstly training multi-stage random forest classifiers with sources of known types in the literature. This was followed by a preliminary classification of the Gaia data and a second training phase that included a selection of the first classification results to improve the representation of some classes. We then applied the improved classifiers to the Gaia data to generate the list of candidates for the variable catalog (Rimoldini et al. 2019).

TESS represents the newest generation of exoplanet missions, and new discoveries can be expected in many fields of astronomy, similarly as it happened with the Kepler and K2 missions. TESS is observing almost the full sky in 27-day long sectors. With its ~17 mag faint limit, all the Cepheids in the Galaxy (that are otherwise not obscured), plus and the brightest ones in the Magellanic Clouds are all observable. TESS measures pre-selected targets in short cadence mode, which have been proposed by the various working groups of the TESS Science Consortium. The target selection of Cepheid and RR Lyrae stars has been led by myself. I gave an invited talk about the potential of the TESS mission concerning Cepheids and RR Lyrae stars at the TASC3/KASC10 Workshop in 2017.

The mission started in late 2018. The TESS Asteroseismic Science Operations Center will provide photometry of the full-frame images and stellar classification as well, but the work is still in progress. I contributed to the latter task. The "first light papers" of the RR Lyrae and Cepheid Working Group are in preparation, I am leading the publication of the results on Cepheid stars observed by TESS. Our preliminary results have been presented at the TASC5/KASC12 Workshop and at the TESS Science Conference in 2019, and I gave an invited talk at the "Stars and their variability observed from space"conference as well. One of the main results is the instability of the pulsation in the bright southern Cepheid, beta Dor.

Dissemination of the results

I authored 18 papers directly connected to the grant, 9 of those in journals with impact factors. I was first author in 6 (3 with IF) of them. I was featured in the Hungarian journal Élet és Tudomány as researcher of the week in 2018. I gave two invited review talks, and presented numerous posters at various conferences.

Grants and awards, achievements

I was awarded with the Bolyai János Research Scholarship to investigate space-photometric data of classical variable stars. I received the Excellent Researcher of the CSFK Awards in 2017, 2018 and 2019. I served as a SOC member at the RRL2019 conference.

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