Project closing report

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Classical pulsators and the Blazhko effect

The major achievements of the project concern RRL stars. The Blazhko modulation and the photometric and spectroscopic metallicities are investigated and new properties of RRL stars are also identified.

1 Blazhko stars

The extended BVI_C photometry and the non-calibrated time series of the most crowded stars published in Jurcsik et al. (2017) enabled us to analyse the complete Blazhko RRL sample of the M3 globular cluster. This is the largest multi-colour photometric data set of a homogeneous group of Blazhko stars ever observed, which is suitable to detect any connection, if it exists, between the properties of the modulation (the variations of the pulsation changes during the modulation cycle) and the physical parameters of the variables. Moreover, the comparison of the results with the data of the single-periodic RRL sample of the cluster yields a unique opportunity to detect any systematic difference between regular and Blazhko RRL stars. Our study (Jurcsik, 2019) showed that:

- the relative strength of the modulation of long-period Blazhko stars is typically smaller than in shorter period variables;
- the phase-modulation of Oo-type II variables is week if any;
- the mean light curve of the variables showing weak modulation is close to the light curve of similar period non-modulated stars;
- no direct connection between the physical properties of the stars and their Blazhko characteristics is detected.

Moreover, based on the distribution of the Blazhko variables and on the detection of the onset of the modulation in V119, a previously stable RRab star, we concluded that the Blazhko modulation is not a stable feature of the pulsation of RRL stars, it may appear or disappear in any RRL star at any time, probably. Additionally, we found that the energy of radiation emission averaged over the pulsation period is larger in the large-amplitude Blazhko phase than in Blazhko minimum and most probably, the same is true for the changes of the pulsation averaged kinetic energy. This leads to the conclusion that some additional source of energy storage/release should have to operate during the Blazhko cycle.

In another study (Skarka, Prudil & Jurcsik, 2020) the Blazhko properties of the Galactic bulge RRL stars were investigated using the extended I-band OGLE data. The results are in line with the M3 study, instead of any strict relation between the Blazhko and pulsation amplitudes, periods, and the shape of the light curves, only systematic limits have been detected. The OGLE sample also points out that the Blazhko effect is suppressed in cooler, larger, more luminous RRL stars. The large sample size (3141 stars) made it possible to investigate the distribution of the modulation periods in detail. Our finding is that it can be described with two populations centred at 48 and 186 d and that there is a low density region between them, the Blazhko valley, in the pulsation period-modulation period plane. Based on the shapes of the modulation envelopes six morphological classes of the modulation are identified.

The Kepler non-Blazhko RRL sample was also revisited checking the stability of the light curves (Benkő, Jurcsik & Derekas, 2019). Although the Blazhko effect was identified only in one case, permanently or temporarily excited additional modes, cycle-to-cycle light-curve variation, erratic or cyclic period/phase changes were detected in most of the stars. The origin of these instabilities and their connection to the classical Blazhko phenomenon is not clear.

2 Photometric and spectroscopic metallicities

Stellar metallicity is one of the most crucial parameters in astronomical, astrophysical and cosmological studies, as well. Direct spectroscopic metallicity determinations are often prohibitively costly for large samples of very far, faint objects. Therefore, it is not surprising that several indirect methods using photometric information have been developed to estimate the metallicities of different type stars.

Concerning RR Lyrae stars, the most widely used technique is to calculate the [Fe/H] from simple parameters obtained from the Fourier solution of the light curve. The linear formulae published in Jurcsik & Kovács (1996) and in Smolec (2005), which use V and I-band light-curve parameters of fundamental-mode RR Lyrae stars are estimated to give [Fe/H] values with 0.13-0.18 dex accuracy, however, the inherent systematic biases of the method have never been investigated systematically. Therefore, we performed a thorough check of the compatibility and accuracy of the results of the V- and I-band photometric metallicity formulae using mono-metallic globular cluster data (Jurcsik, Hajdu & Juhász, 2021).

After transforming the two formula to the same $[\mathrm{Fe/H}]_{\mathrm{UVES}}$ (Carretta et al., 2009) metallicity scale, we have found that, on the average, the photometric metallicities of OoI variables are less metal-poor than for Oo-type II variables in the V band, and less significantly but an opposite sign difference is detected in the I band. Consequently, the V-band photometric [Fe/H] is, in general, about 0.05 dex more metal-poor than the I-band results for globular cluster data. The reason for this offset is that the sample is dominated by Oo I stars, and the formulae yield results with the opposite sign differences for stars belonging to the two Oo types in the two photometric bands.

As a by-product of this study we can strengthen one of the results published by Prudil et al. (2019), namely that the Oo II sample of RRab stars in the Galactic bulge is about 0.1 dex more metal-poor than the Oo I group. As the $[\mathrm{Fe/H}]_{\mathrm{phot}}$ derived from I-band data of Oo II stars has been found to tend to be less metal-poor than of the Oo I stars in mono-metallic systems, this systematic bias of the method is of the opposite direction that was detected by Prudil et al. (2019) in the bulge.

The accuracy of an empirical relation between different observables depends on the accuracy of the input data that the calibration of the formula is based on, and also on the limits of the inherent physical connection between the compared quantities. Concerning the calibration of the photometric metallicity, the most problematic issue is the accepted [Fe/H] values of stars in the calibrating sample. The scatter of the different spectroscopic [Fe/H] data of the calibrating stars that are used to establish a photometric metallicity formulae is about 0.15 dex, typically, i.e., this is of the same order as the accuracy of the calculated photometric metallicities.

The metallicities of globular clusters seem to have reached a consensus already. In spite of that spread in the iron content in globular clusters has been revealed in some clusters, but its range typically does not exceed 0.1-0.2 dex and/or the population of the extreme metallicity stars is marginal in most cases (see e.g. Table 8 in Marino et al., 2021). Therefore, we have made an attempt to establish new photometric metallicity formulae using globular cluster data, exclusively (Jurcsik & Hajdu, 2023). The G-band time-series data of RRab stars published in the third data release (DR3) of the Gaia collaboration were utilized.

The literature data of globular clusters' [Fe/H] values were compiled and unified, accepting $\log\epsilon\mathrm{Fe}_\odot = 7.50$ as the solar reference value (Asplund et al., 2009). For the calibration of the metallicity we selected 526 good-quality RRab light curves belonging to 70 globular clusters.

However, using these data, the accuracy of the derived metallicity formula, which involves only the period and the φ_{31} phase parameter, could not be decreased, it remained 0.15 dex. The goodness of the fit could not be improved by using more parameters and/or non-linear formulae either.

When the OoI and OoII samples were separated, the fitting accuracy of the OoI sample decreased to 0.011, but it increased to 0.17 for the OoII sample. It seems that the Oo-type II sample of RRab stars does not follow any photometric metallicity relation strictly. Oo-type II stars, most probably, have already evolved off the zero age horizontal branch (ZAHB), and their physical structures may show larger diversity than the structures of RRLs close to the ZAHB evolutionary stage. This might be the reason for the decreased efficiency of the photometric metallicity formula for Oo-type II variables than for Oo-type I stars.

The comparison of our [Fe/H] estimates with published Gaia G-band photometric metallicities of RRab stars has led to the conclusion that none of the photometric metallicity formulae valid in this band yields similarly accurate [Fe/H] values all along the possible metallicity range. Correcting for the significantly different zero points of the different photometric metallicity calibrations, each formula tends to over- and under-estimate the metallicity at the high and at the low metallicity ends of the possible metallicity range.

Concerning the spectroscopic iron abundance determinations of RRL stars we have pointed out the importance of using the temporal surface gravity values instead of the static ones (Kovács, Jurcsik, 2023). The higher quality of the gravity-corrected metallicities is also strongly supported by the tighter correlation with the metallicities predicted from the period and Fourier phase, φ_{31}. This work highlights the need for using some external estimates of the temporal gravity in the chemical abundance analysis, rather than relying on a full-fetched spectrum fit that leads to large correlated errors in the estimated parameters.

3 Binarity and other special properties of RRL stars

The analysis of the O-C diagrams is a powerful tool for the discovery of RRL binary candidates utilizing the lite-travel time effect, and the OGLE photometry provides excellent data for this purpose. After an initial search for RRL binary candidates (Hajdu et al., 2015) we have undertaken a systematic study of binary RRL variable candidates in the Galactic bulge data.

Alltogether 87 candidate RRLs were detected in binary systems (Hajdu et al., 2021). This sample allowed us to draw the first firm conclusions about the population of such objects: no candidate has an orbital period below 1000 days, while their occurrence rate steadily increases with increasing period, and peaks between 3000 and 4000 days, however, the decrease in the number of stars toward even longer periods is probably the result of observational biases. The distribution of the mass functions is highly peculiar, exhibiting strong trimodality. We interpret these modes as the presence of three distinct groups of companions, with typical inferred masses of $\sim 0.6, \sim 0.2$, and ~ 0.067 $M_{\odot}$, which can be associated with populations of white dwarf and main sequence, red dwarf, and brown dwarf companions, respectively.

The periods and the light-curve amplitudes/shapes of RR Lyrae stars depend on the physical properties of the stars. Based on observational and theoretical evidences, one would assume that the light-curve shapes of RRL stars, neither of similar nor of different metallicities, are completely identical at different pulsation periods. Therefore, the finding that RRab variables with identical light-curve shapes even in different wavelength bands at different pulsation periods do exist (Jurcsik, Juhász, 2022), needs an explanation. To show such identical-shape light variations the complete dynamical structures of these stars have to be very similar. However, the different metallicity (as indicated by the photometric metallicity formula), and consequently the opacities of the atmosphere of these stars makes it very unlikely. The shocks, forming the shapes of the bump, and the hump features of the light curves are not expected to behave so similarly in RRLs with noticeably different fundamental parameters, either. Therefore, to explain the light curve similarity of these pairs of variables is a challenging task for modelling RRL pulsation.

In a very recent paper (Hajdu et al., 2024, submitted to Nature Astronomy), we have reported evidence for circumstellar material around RRL stars.

4 Modelling and other achievements

The eight convective parameters involved in 1D pulsation hydrocodes i.e., the Budapest-Florida code (Kolláth et al., 20102) and the MESA-RSP (Smolec & Moskalik, 2008) have been calibrated for fundamental (RRab) and first overtone (RRc) RR Lyrae variables (Kovács, Nuspl & Szabó, 2023, 2024), and new parameter sets were recommended. Detailed comparison of model computations for several selected stable RR Lyrae stars of the globular cluster M3 based on the observations published by Jurcsik et al. (2017) was performed. Although we have succeeded in narrowing down the deviation in the details of radial velocity variations, the codes cannot provide the observed luminosity variations parallel with comparable accuracy. This discrepancy means that both codes have some missing physical processes in the energy transport toward the stellar surface and the working of pulsating stars.

The Gaia parallaxes (EDR3) were checked against evolutionary and pulsation model estimates of luminosities of double-mode and single-mode RRL stars (Kovács, Karamiqucham, 2021b,a). Although the RRd results indicated an overall shift of +0.02 mas for the EDR3 parallaxes, the results for single mode variables showed an excellent agreement with the Gaia parallaxes.

Thirteen new multi-mode Cepheids were identified using the database of the ASAS-SN survey (Jurcsik, Hajdu & Catelan, 2018), which increased the number of Galactic disk multi-mode Cepheids by 33%.

Results on the TESS observations of RRL stars, and Cepheids were published by Benkő et al. (2023); Plachy et al. (2021) and by Molnár et al. (2022).

Overtone RR Lyrae stars were also studied. Detailed spectroscopic and photometric investigations of RRc stars appeared in two papers (Benkő et al., 2021a,b) and K2 data of RRc stars were analyzed by Netzel et al. (2023). The Blazhko type RRc stars in the Stripe 82 region were analysed be Varma, Benko and Ngeow (2024). Similarities between the frequency patterns of RRc and RRab stars showing the peculiar $f_{.68}$ frequencies were documented Benkő & Kovács (2023).

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