Baade-Wesselink Analysis of RR Lyrae Stars in the Globular Cluster M3

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An extended photometric and simultaneous spectroscopic observation campaign measuring time-series data of the variables in the M3 globular cluster was conducted in 2012. The obtained BVI_{C} light curves have good modulation-phase coverage for most of the Blazhko variables, and the spectroscopic data provide the largest sample of radial velocity (RV) curves of RR Lyrae (RRL) stars ever obtained. These data have made it possible to perform Baade-Wesselink (B-W) analysis of dozens of regular variables and to show why the B-W technique cannot be applied for stars exhibiting the Blazhko effect.

1 Goals/Observations

Aiming to compare B-W distances of RRL stars in the M3 globular cluster with the cluster's distance derived from other methods, and to check the applicability of the B-W method on Blazhko stars, a coordinated spectroscopic and photometric observation campaign was conducted in 2012. The photometric data were gathered with the 90/60 cm Schmidt telescope at Piszkéstető by the staff members of the Konkoly Observatory, and the spectra were obtained with the Hectochelle@MMT in Arizona (USA) by G. Fűrész and K. Kolenberg. The data and some of the results were published in Jurcsik et al. (2015, 2017) and in Jurcsik & Hajdu (2017).

2 Results on Stable RRL Stars

As a result of the B-W analysis of 26 stable light-curve RRL stars, a mean value of 10.5 ± 0.3 kpc for the distance of the cluster (distance modulus $\nu = 15.10 \pm 0.05$ mag) was derived. This is in good agreement with other distance estimates of M3, e.g., the Harris (1996) catalogue (2010 edition) lists $\nu = 15.07$ mag.

The radii of the RRL stars determined by the B-W process are in perfect agreement with model predictions published by Marconi et al. (2015).

The large sample of the RV curves made a detailed comparison of the light and velocity curves possible. The most significant discrepancy between the Fourier parameters of the time-series V and RV data appears in the phase differences. The full range of the phase differences of the RV curves is systematically smaller than for the V light curves. While the full range of the φ_{21} phase-difference values of the RV curves is only about 0.2 rad and no tendency of any variation with increasing pulsation period is evident, the φ_{21} values of the light curves cover larger than 0.6 rad phase range and they are increasing with increasing period monotonically. Most probably, the difference between the shapes of the V and RV curves in the

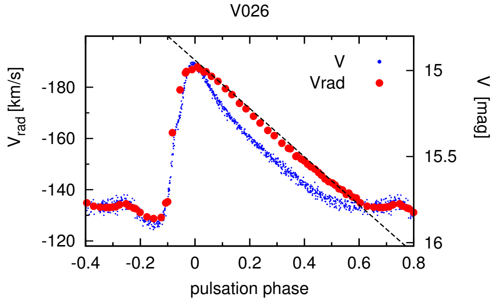

Fig. 1: Comparison of the V and RV curves of a stable light-curve RRab star in M3.

$0.0 - 0.6$ pulsation phase interval, which corresponds to the declining branch of the light curve, is the explanation of the relative constancy of the phase differences of the RV curves. In contrast with the curved shape of the light curve, the RV curve is close to linear in this phase interval as shown in Fig. 1.

The amplitude and phase relations between the variations of the physical properties of RRL stars are sensitive indicators of stellar atmosphere properties and are important observables for asteroseismological studies (Castor, 1968; Moya et al., 2004; Szabó et al., 2007). They also yield effective tools for checking hydrodynamical models and hold information on the spherical harmonic orders of non-radial modes. However, both observational and model results of the amplitude and phase relations of RRL stars are very sparse or lacking.

As for the amplitudes, the period-amplitude diagram (Bailey et al., 1919) is the only well known and studied relation. In addition, a linear formula connecting the amplitudes of the pulsation velocity and the V-band light curve was determined by Liu (1991) using a sample of 23 field RRab stars.

The homogeneous sample of the M3 variables shows that, indeed, the amplitude of the RV curve varies with increasing pulsation period similarly to the change in the amplitude of the light curve, but the formula relating the amplitudes of the RV and V curves is quadratic, not linear (see Fig. 2). The relation between the amplitudes of the radius variation and the light curve is also quadratic. The panels of Fig. 2 also show that the amplitude relations of the overtones differ from the relations defined by the fundamental-mode RRab stars.

The times of maximum temperature/maximum brightness and the minimum radial displacement/zero expansion velocity are not identical in classical pulsators. As a consequence of the non-adiabaticity and non-linearity of the pulsation, a phase lag between these extrema occurs. The only information on the phase-lag between the RV and V curves of RRL stars was published by Ogłoza et al. (2000). Using the RV and photometric data of Galactic field RRab stars collected by Kovács (2003), they reached the conclusion that the $\varphi(\mathrm{RV}) - \varphi(V)$ phase lag of RRL stars does not depend on the pulsation period and/or amplitude; it is uniformly -0.19.

The M3 data show, however, that the phase difference between the RV and the brightness variations of RRL stars depends on the period (left-hand panel in Fig. 3). For comparison, the data used by Ogłoza et al. (2000) are also plotted in the right-hand panel of Fig. 3; different symbols denote different metallicity groups of the heterogeneous sample of field RRL stars in this panel. The phase lag corresponds

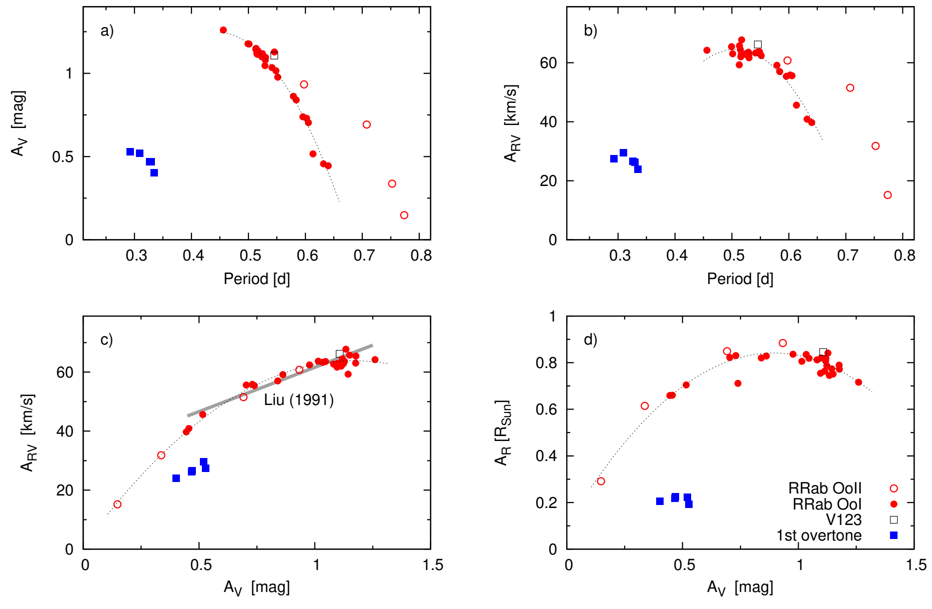

Fig. 2: Full amplitudes of the V light curve (a) and the RV curve (b) versus pulsation period and amplitudes of the RV (c) and radius (d) changes versus the V-band amplitude of RRL stars in M3 are shown in the top and the bottom panels, respectively.

to the phase difference between the 1st-order components of the Fourier solutions in both plots. The phase-lag ranges covered by the M3 data and of the field stars are similar, and the phase lags of the different metallicity groups of the field sample indicate some tendencies of period dependence also, similar to the M3 sample. Consequently, the inhomogeneity of the field stars is the reason why the phase-lag – period relation has not been detected previously.

The special, anomalous light-curve shape, non-Blazhko star, V123, which was discussed in detail in Jurcsik et al. (2013, 2017), is also displayed in Fig. 2, and Fig. 3.

3 On the Applicability of the B-W Technique on Blazhko RRL Stars

The phase coverage of the RV data made it possible to apply the B-W technique on about two dozens of Blazhko RRL stars in one or two phases of the modulation. The analysis of Blazhko stars led, however, to an unexpected result. It turned out that the spectroscopic radius ($R_{\rm sp}$) curve, derived from the RV data, and the photometric radius ($R_{\rm phot}$) curve, determined from the photometric data using synthetic model atmosphere results (Castelli & Kurucz, 2003), have different modulation properties for Blazhko stars. The $R_{\rm sp}$ follows the amplitude and phase changes of the light and the RV curves, but $R_{\rm phot}$ remains stable, neither amplitude nor phase modulation of the derived $R_{\rm phot}$ curves is detected.

The basic assumption of the application of the B-W technique is that the line-of-sight radius ($R_{\rm sp}$) variation and the angular-diameter (θ) changes reflect the same

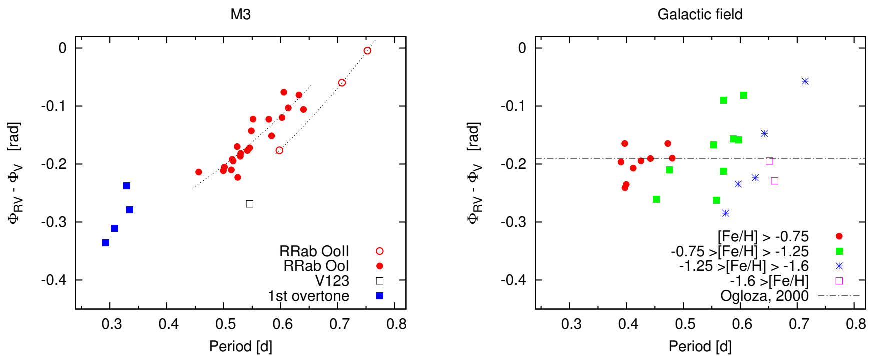

Fig. 3: Phase lags between the RV and the V light curves of the M3 variables (left-hand panel) and of Galactic field RRab stars (right-hand panel).

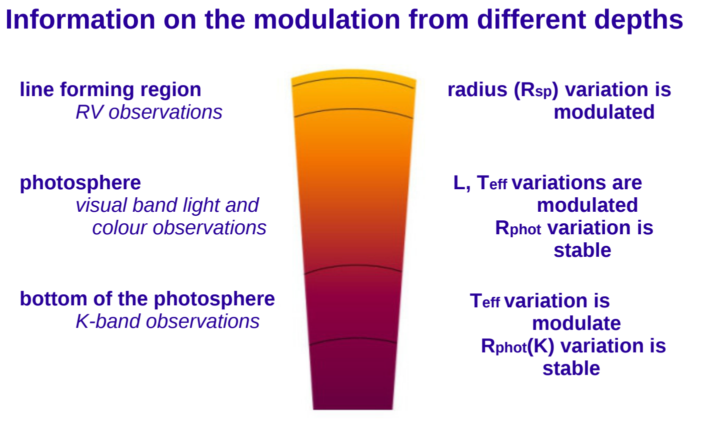

Fig. 4: A schematic picture of the appearance of the Blazhko modulation in different-depth layers of the atmosphere.

radial displacement of the atmosphere ($R_{\rm sp} = R_{\rm phot} = d\theta$; d is the distance of the star). However, if the $R_{\rm sp}$ and $R_{\rm phot}$ curves are different, as it was detected in Blazhko stars, this criterion of the applicability of the B-W method is not met in these stars.

The detected conflict between the variations of $R_{\rm sp}$ and $R_{\rm phot}$ shows that the modulation properties of the different depth layers of the atmosphere are different, as it is shown in Fig. 4 schematically. The RV data, which provide information on the dynamics of the uppermost, line-forming regions, show that the radial displacement of these layers are strongly modulated. The observed light and colour variations emitted by the photosphere are also modulated, however, the $R_{\rm phot}$ data (derived from the photometry) indicate that the radial displacement of the photosphere is not affected by the modulation. The deepest layers of the photosphere are seen in the infrared bands as a consequence of the infrared dip in the opacity. The very recent finding that the detected small amplitude modulation of the K-band light curve of RR Lyrae stars is connected exclusively to the modulation of the temperature variation while the radius change of the pulsation remains stable (Jurcsik et al., in preparation) confirms the results obtained from the B-W analysis of Blazhko stars.

The first B-W analysis of Blazhko stars has led to the following conclusions:

- the modulation properties are depth dependent;
- the radius variation at different depths are desynchronised; the most synchronous phase of the modulation occurs at around mean-amplitude pulsation, contrary to that it was supposed to appear at around the minimum phase of the modulation by Gillet (2013) and Chadid & Preston (2013);
- the stability of the radial movement of the deeper photospheric regions indicates that the observed phase modulation does not reflect pulsation-period changes of the radial-mode, in contrast with previous suggestion of e.g. Chadid & Preston (2013) and Chadid et al. (2014).

These findings provide strong constraints on any possible Blazhko model.

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