Classical Pulsators: Contrast Between Pulsation Modes

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We comment on the differences between classical pulsators, Cepheids and RR Lyrae stars, in which the dominant variability is due to radial fundamental mode and due to radial first overtone mode. We consider the occurrence of periodic modulations of pulsation, excitation of additional low-amplitude periodicities and overall stability of the stars pulsating in the two radial modes.

The dominant variability in classical pulsators, Cepheids and RR Lyrae stars, is due to large-amplitude pulsation, either in the radial fundamental (F) mode, or in the radial first overtone (1O) mode. The instability strip for first overtone pulsators is hotter and is limited in luminosity. At the same position in the HR diagram, the first overtone period, $P_{1\mathrm{O}}$, constitutes an $0.70-0.74$ fraction of the fundamental mode period, P_{F}. Light curves characteristic for the two modes are also different: fundamental mode pulsation is typically of larger amplitude and more *nonlinear*; rising branch is steeper and light curve shape is more triangular as compared to first overtone pulsation. Period-luminosity relation, location in the color-magnitude diagram and light curve shape, quantified via the Fourier decomposition parameters, usually allow us to unambiguously discriminate between the two pulsation modes.

The two classes, fundamental and first overtone pulsators, also differ when other properties of pulsation are considered: occurrence of periodic modulation of pulsation, excitation of additional, low-amplitude periodicities, beyond the dominant radial one, and overall stability of pulsation.

Quasi-periodic modulation of pulsation amplitude and/or phase is a common property of fundamental mode RR Lyrae (RRab) stars and is known as the Blazhko effect (Blažko, 1907). Top-quality ground-based observations and observations of space telescopes indicate that incidence rate is close to 50 % in RRab stars (eg. Jurcsik et al., 2009; Benkő et al., 2010). Kovacs (2018) concluded, based on analysis of *Kepler* data, that even all RRab stars may be modulated; for the critical review of this claim see however Benkő et al. (2019). Space observations led to the discovery of the period-doubling effect (alternating deep and shallow brightness maxima/minima) at some phases of the modulation cycle in a fraction of modulated RRab stars (Kolenberg et al., 2010; Szabó et al., 2010). In the frequency spectrum, period doubling effect manifests as signals close to subharmonic frequencies, ie. $(2n+1)/2f_{\mathrm{F}}$ ($f_{\mathrm{F}}=1/P_{\mathrm{F}}$).

Periodic modulation of pulsation is also detected in first overtone RR Lyrae (RRc) stars, the incidence rate is much lower however. Space observations of RRc stars are too scarce to draw reliable statistics. For the ground-based Galactic bulge OGLE data the incidence rate is 5.6 % (Netzel et al., 2018). Period doubling effect was not yet detected in Blazhko RRc stars.

For classical Cepheids, periodic modulation of pulsation was discovered only recently. Just as in the case of RR Lyrae stars, the effect is more frequent in F mode pulsators. Low-amplitude modulations of light curve shape were reported for the only genuine F-mode Cepheid in the original *Kepler* field, V1154 Cyg (Kanev et al., 2015; Derekas et al., 2017), followed by the discovery of periodic modulation of pulsation in 51 F-mode Cepheids in the Magellanic Clouds observed by the OGLE project (Smolec, 2017). Interestingly, in the SMC and for pulsation periods close to 10 d ($12 < P_{\rm F} < 16$ d) the incidence rate of modulated stars is almost 40 %. The incidence rate is significantly lower for the LMC – up to 5 % for $8 < P_{\rm F} < 14$ d. Still, the analysis of OGLE data indicates that periodic modulations may be quite common in classical F-mode Cepheids with periods close to 10 d.

For single-periodic 1O Cepheids, periodic modulation was not firmly detected yet. While additional low-amplitude signals are quite often detected close to the radial mode frequency, they are reported on one side on the radial mode frequency only (eg. Moskalik & Kolaczkowski, 2009; Süveges & Anderson, 2018). Triplets, or multiplets, signatures of modulation in the frequency spectrum, were not detected in 1O Cepheids so far, except one marginal case (Kotysz & Smolec, 2018). Interestingly, periodic modulation of pulsation was reported in double-overtone Cepheids, pulsating simultaneously in radial first and second overtones (Moskalik & Kolaczkowski, 2009).

While modulations seem to dominate in F-mode pulsators, additional, low-amplitude periodicities are more common in 1O pulsators, and are very scarce or even absent in F-mode stars. In RRc stars, a few new classes of double-periodic pulsations were reported – for a review see Smolec et al. (2017). It seems that additional periodicities for which period ratios, $P_{\rm x}/P_{\rm 1O}$, are in the $0.60 - 0.64$ range (see eg. Gruberbauer et al., 2007; Olech & Moskalik, 2009) may be an intrinsic property of RRc stars. Nearly 1000 such stars were reported in the analysis of OGLE Galactic bulge data, which gives an incidence rate of 8.3 % (Netzel & Smolec, 2019). When top-quality ground-based data are considered, ie., most densely sampled fields of the OGLE project, the incidence rate raises to 27 % (Netzel et al., 2015). Finally, nearly all RRc stars observed from space show this form of variability (eg. Szabó et al., 2014; Moskalik et al., 2015; Molnár et al., 2015; Kurtz et al., 2016).

Interestingly, the same form of double-periodic pulsation, with period ratios, $P_{\rm x}/P_{\rm 1O}$, in the $0.60 - 0.65$ range is observed in first overtone classical Cepheids (eg. Soszyński et al., 2008; Smolec & Śniegowska, 2016). Incidence rate is also relatively high; around 10 % (Süveges & Anderson, 2018), however systematic and in-depth study of first overtone classical Cepheids is still to be completed (Ziółkowska, Styczeń & Smolec, these proceedings). Except just described signals, additional low-amplitude periodicities with frequencies close to the first overtone frequency are common in 1O Cepheids (Moskalik & Kolaczkowski, 2009; Süveges & Anderson, 2018).

For F-mode pulsators, additional, low amplitude periodicities are scarce. Prudil et al. (2017) reported additional shorter-period variability in RR Lyrae stars, the majority of them originally classified as RRab. These stars seem to form a short period, low period-ratio extension of the RRd sequence, however excitation of two radial modes, F and 1O is unlikely. Additional variability is of relatively large amplitude and the nature of this group remains puzzling.

Additional, low-amplitude periodicities are detected in modulated RRab stars observed from space. In particular, the period-doubling effect manifests as signals at half-integer frequencies, but other periodicities are also detected (Molnár et al., 2017). Interestingly, in non-modulated RRab stars observed with *Kepler* no additional low-amplitude periodicities are reported. Benkő & Szabó (2015) hypothesize that the Blazhko effect and excitation of additional low-amplitude periodicities in RRab stars are intrinsically connected (see however Benkő et al., 2019).

Precise and continuous monitoring of classical Cepheids from space allowed to study cycle-to-cycle variability. Besides low-amplitude periodic modulations in the light curve of V1154 Cyg, observed with *Kepler*, Evans et al. (2015) analysed *MOST* observations of F-mode and 1O-mode Cepheids and reported cycle-to-cycle variations in the latter, concluding that pulsation in first overtone pulsator is less stable than in the F-mode Cepheid. No similar effect was found in the observations of a few classical Cepheids with *CoRoT* (Poretti et al., 2015).

Long monitoring of classical pulsators by ground-based surveys, such as MACHO or OGLE, allowed to study the stability of pulsations on long time scales. Period changes due to evolution in the HR diagram, across the instability strip, are expected, but these are very slow and should be monotonic. Surprisingly, in a significant fraction of stars irregular period changes are observed on a much shorter time scale than expected due to evolution, see eg. Berdnikov et al. (1997); Poleski (2008). Poleski (2008) checked the variability in the $O-C$ diagrams on the time scale of a few years and found that period changes are more frequent in first overtone pulsators than in the fundamental mode ones. In addition, the changes in the $O-C$ diagrams are often non-linear or random fluctuations.

In the frequency analysis of first overtone RR Lyrae stars and classical Cepheids unresolved power at the position of first overtone frequency is often detected and it usually corresponds to irregular period changes (eg. Netzel & Smolec, 2019; Smolec & Śniegowska, 2016). These changes were not studied in detail however. Such changes are not so frequent in fundamental mode pulsators, at least not in classical Cepheids (Smolec, 2017).

Here we want to quantify the effect using a rough, automatic analysis of OGLE-IV data for the Magellanic Clouds (Soszyński et al., 2015, 2016). In the analysis we use only stars with at least 100 brightness measurement and with the total length above 2200 d, which means that for all stars we consider seven observing seasons and study the stability on a time scale of a few years. For each star, we (i) determine the dominant, radial pulsation frequency with discrete Fourier transform; (ii) fit the data with Fourier series of the following form:

$$m(t) = A_0 + \sum_{k=1}^{N} A_k \sin(2\pi k f t + \phi_k)\,,$$

with order, N, chosen to satisfy $A_k/\sigma(A_k) > 4$ for all terms of the decomposition; (iii) remove possible slow trends by fitting second order polynomial to the residuals, as well as remove severe ($> 6\sigma$) outliers from the data and, finally; (iv) analyse the frequency spectrum of the residuals, in particular, focus on the direct vicinity of the radial mode frequency.

Pulsation is considered non-stationary when significant (S/N > 4) unresolved ($|f - f_{\rm rad}| < 2/\Delta T$; ΔT – data length) power is detected at direct vicinity of the radial mode frequency, $f_{\rm rad}$. Solid line in Fig. 1 shows period distributions of all analysed classical Cepheids in the LMC (top row) and in the SMC (bottom row) for the fundamental mode (left panels) and for the 1O mode (right panel). Dashed

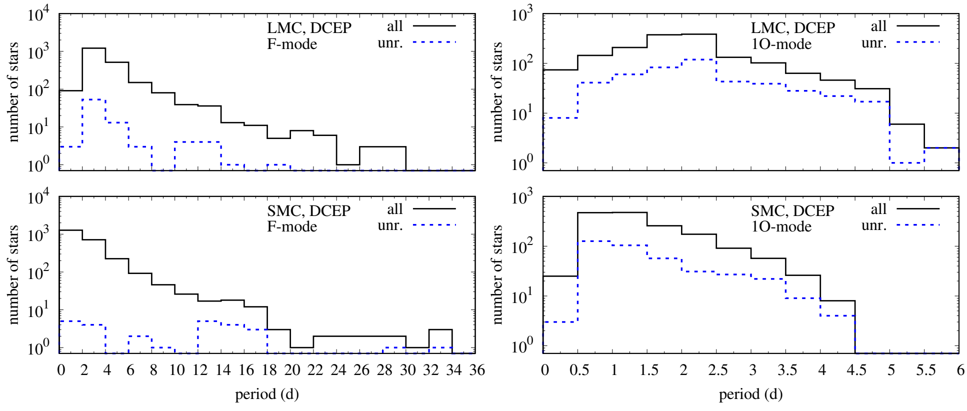

Fig. 1: Period distribution for the analysed classical Cepheids (solid line) and for stars with non-stationary pulsations detected (dashed lines). Data for the LMC and the SMC are presented in the top and in the bottom rows, respectively. Data on F mode and 1O mode pulsators are shown in the left and right panels, respectively.

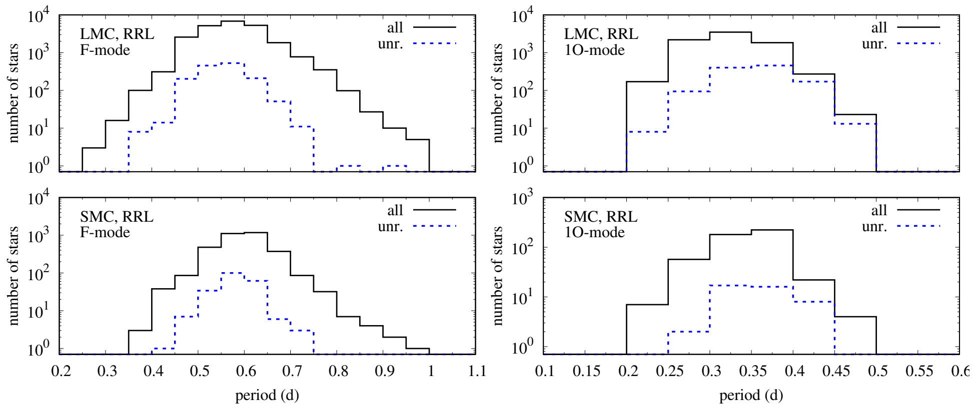

Fig. 2: The same as Fig. 1, but for RR Lyrae stars.

line shows period distribution for stars with non-stationary pulsations. Fig. 2 is an analog of Fig. 1 for RR Lyrae stars. Tab. 1 lists the incidence rates for non-stationary pulsation and the considered classes of pulsators, systems and dominant pulsation modes.

A caution is needed when considering the results: our analysis is very simplified. In particular, we do not prewhiten the data with additional signals that are expected in a significant fraction of stars: those arising due to modulation and due to other periodicities in the data, more complex trends, or arise due to possible instrumental effects. In particular, Blazhko effect in RR Lyrae stars may manifest as large-amplitude side peaks in the frequency spectrum. Consequently, the overall noise level increases in the data, and non-stationary pulsation may not be detected. In the ground-based, seasonal OGLE data, daily and yearly aliases may add to the confusion and may mimic non-stationary pulsation if accidentally fall at the vicinity

	DCEP/F	DCEP/1O	RRab	RRc
LMC	3.8 %	29.6 %	6.3 %	14.3 %
SMC	1.1 %	24.2 %	6.3 %	8.7 %

Tab. 1: The incidence rates of non-stationary pulsators among F and 1O classical Cepheids (DCEP) and RR Lyrae stars in the Magellanic Clouds.

of the prewhitened radial mode frequency. For these reasons, results presented in the Figures and in the Table just indicate the overall tendencies and point toward differences between the two pulsation modes, but provide no quantitative and unbiased statistics on the occurrence of non-stationary pulsations.

There are many phenomena that may produce unresolved power at the radial mode frequency after prewhitening. These include periodic modulations of pulsation on time scales longer than $\Delta T/2$, arising eg. due to long-period Blazhko modulation or due to light time travel effect in a binary system, but these phenomena are rather scarce. Pulsation period is expected to change due to evolution, but the expected time scale is much longer than the length of considered data. In the majority of cases, the unresolved signal is due to irregular phase changes and, less frequently, amplitude changes, on the time scales comparable to data length. A more thorough analysis is needed however to quantitatively and systematically describe these effects. Still, some interesting points can be made. Considering Cepheids (Fig. 1) the emerging picture is quite clear. Non-stationary pulsations are very frequent for 1O pulsators and are scarce for F-mode pulsators. For F-mode Cepheids only single stars with non-stationary pulsations were detected without any preference for particular period range. To the contrary, significant fraction ($20-30$ %) of 1O pulsators show non-stationary pulsations on the considered time scale and their period distribution follows the distribution for all stars.

For RR Lyrae stars (Fig. 2) the situation is not that clear, which may be related to large-amplitude additional signals, eg. due to Blazhko effect, that were not prewhitened. Results in Tab. 1 indicate that non-stationary pulsation is still more common among 1O pulsators, but the difference with respect to F-mode pulsators is small. Also in Fig. 2 we can notice that period distributions for stars with non-stationary pulsations follow the period distributions for all stars for both F and 1O pulsators.

Results for both Magellanic Clouds are similar.

To summarise, periodic modulations of pulsation are more frequent in F-mode pulsators, while additional low-amplitude periodicities are more frequent in 1O pulsators. Overall, the 1O pulsation is less stable: irregular phase and amplitude changes on a time scale of a few years are more common among 1O stars.

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