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Are RRab stars fully radial?

József M. Benkő and Róbert Szabó

Konkoly Observatory, MTA CSFK,
Konkoly Thege M. u. 15-17., H-1121, Budapest, Hungary
email: benko@konkoly.hu, rszabo@konkoly.hu

Abstract. Thanks to the space missions *CoRoT* and *Kepler* new oscillation frequencies have been discovered in the Fourier spectra of Blazhko RR Lyrae stars. The period doubling (PD) yields half-integer frequencies between the fundamental mode and its harmonics. In many cases the first and/or second radial overtone frequencies also appear temporally. Some stars show extra frequencies that were identified as potential non-radial modes. We show here that all these frequencies can be explained by pure radial pulsation as linear combinations of the frequencies of radial fundamental and overtone modes.

Keywords. Stars: oscillations, stars: horizontal-branch, stars: variables: other

The first RRab star in which non-radial mode was reported is the *CoRoT* target V1127 Aql. Chadid et al. (2010) explained 468 frequencies detected in this star by four independent frequencies, f_0, f_m, $f' = 2f''$, f_m1, and their combinations. The f_0 and f_m mean the main pulsation and modulation (Blazhko) frequency, respectively, f' (or f'') is the frequency of an independent, possibly non-radial mode, and f_m1 is a secondary modulation frequency acting on 'additional modes' only (see Chadid et al. 2010 for the details). Later on, frequencies of possible non-radial modes have been found in the Fourier spectra of the Blazhko stars CoRoT 105288363 and V445 Lyr, V354 Lyr and V360 Lyr observed by *Kepler* (Benkő et al. 2010 = B10; Guggenberger et al. 2012 = G12). Many frequencies of these modes were found between the position of the radial first overtone and the PD frequencies and yielded period ratios P/P_0 around 0.7.

We homogeneously re-analyzed light curves of all the *CoRoT* and *Kepler* Blazhko RRab stars in which non-radial mode(s) were reported. We used the *CoRoT* 150-days-long data coadded to get 8-min sampling and *Kepler* 3-years-long long-cadence (30-min sampling) data covering Q1-Q12. The *CoRoT* white fluxes were cleaned and de-trended. In the case of *Kepler* targets, we used the raw pixel frames applying our own proper tailor-made apertures for each star and quarter separately (see Benkő et al. 2013). The data were pre-whitened with the main pulsation frequencies and their harmonics, the modulation frequencies and as many modulation side peaks as possible. The resulting Fourier spectra and the frequency solutions from the literature are compared.

V1127 Aql (CoRoT 100689962). Our identification of f_0 and f_m are the same as in Chadid et al. (2010), but if we assume $f'' = f_2 - f_0$, then $f' = 2(f_2 - f_0)$, where $f_2 = 4.825397\,\mathrm{d}^{-1}$ is the frequency of the radial second overtone with the period ratio of 0.582. This identification eliminates the non-radial mode with its period ratio of 0.696. Poretti et al. (2010) have already noticed that V1127 Aql shows half-integer frequencies. If we accept the PD paradigm (Szabó et al. 2010), the frequency f_m1 can also be interpreted as a linear combination: $1.5f_0 - f'$.

G12 found the following independent frequencies of *CoRoT 105288363*: f_0, f_m, f_s (secondary Blazhko frequency), f_1, f_2, first and second radial overtone modes with the period ratios 0.745 and 0.590, respectively, and two non-radial modes, $f_\mathrm{N} = 2.442\ \mathrm{d}^{-1}$ ($P_\mathrm{N}/P_0 = 0.722$) and $f_\mathrm{N2} = 2.2699\,\mathrm{d}^{-1}$. The multiple and time-dependent modulation of

this star makes its frequency spectrum complicated. We removed more side peaks than G12, so we obtained a bit different peak structure. Now, the peak at $f_{\rm N2}$ seems to be insignificant while $f_{\rm N}$ can be identified as $2(f_2 - f_0)$.

In the case of *V445 Lyr (KIC 6186029)* G12 reported f_0, $f_{\rm m}$, $f_{\rm s}$, $1.5f_0$ (PD), f_1, f_2 and non-radial mode $f_{\rm N} = 2.7719$ d^{-1} ($P_{\rm N}/P_0 = 0.703$). Many similarities between CoRoT 105288363 and V445 Lyr have been discussed by G12. In this study we find an additional one: the previously suggested non-radial mode $f_{\rm N}$ can also be identified as $2(f_2 - f_0)$.

According to B10, frequency content of *V354 Lyr (KIC 6183128)* is the following: f_0, $f_{\rm m}$, f_2 ($P_2/P_0 = 0.586$); two independent non-radial modes, $f' = 2.0810$ d^{-1} and $f''' = 2.6513$ d^{-1}, and $f'' = 2.4407$ d^{-1} which was identified as a possible radial first overtone mode with the period ratio of 0.729. The frequency spectrum of the Q1-Q12 data is a bit different from that for Q1-Q2 data (B10), because the amplitudes of the additional modes strongly depend on time (B10, Szabó et al. 2013) and we removed more side peaks around harmonics eliminating more aliases. In consequence, the f'' frequency became insignificant. We explain $f' = (f_0 + f_1)/2$, where $f_1 = 2.3843$ d^{-1} and $f''' = 1.5f_0$ (PD). We detected two additional significant peaks at 2.999 d^{-1} and 2.300 d^{-1} which produced an equidistant triplet with the main PD frequency f'''.

Frequency solution for *V360 Lyr (KIC 9697825)* from B10 is f_0, $f_{\rm m}$, f_1 (first overtone mode with the period ratio $P_1/P_0 = 0.721$), and $f' = 2.6395$ d^{-1}, an independent non-radial mode. The star shows a consistent picture with the similar stars if we identify f' and its side peaks as a PD effect, and if f_1 is identified as $2(f_2 - f_0)$, where $f_2 = 3.046$ d^{-1}.

Summarizing: (i) Using linear combination frequencies of radial modes we obtained alternative solutions for all those Blazhko RRab stars in which non-radial modes were previously suggested. In other words, our mathematical description explains the spectra solely by radial modes.

(ii) The amplitudes of the harmonics of combinations are many times higher than those of simple combination frequencies e.g. $A[2(f_2 - f_0)] \gg A(f_2 - f_0)$. This is unusual but a similar phenomenon, where the combination frequencies have higher amplitudes than their components, was reported by Balona et al. (2013) for a roAp star.

(iii) We searched for stars which show high-amplitude linear combination frequencies in their Fourier spectra and found at least two additional cases: CoRoT 103922434 and V366 Lyr (KIC 9578833).

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