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Additional modes and cycle-to-cycle variations of non-Blazhko RR Lyrae stars

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Abstract

This paper presents our study on the *Kepler* non-Blazhko RR Lyrae sample. We analysed long and short cadence *Kepler* flux curves with different methods such as studying the Fourier spectra, the Fourier amplitude and phase variation functions, the O−C diagrams and their Fourier contents. We detected significant cycle-to-cylce variations of the short cadence flux curves. Noise or instrumental origin of the effect has been checked and excluded. In addition, we detected low amplitude additional modes for six stars (a third of the sample). Two stars proved to be anomalous RRd stars containing the radial first overtone frequency while the other four ones show the second radial overtone frequency and its linear combinations. The presence of the Blazhko effect was also tested. We found only one possible Blazhko star in this sample which confirms the $\sim 50\%$ Blazhko incidence ratio for the *Kepler* RRab sample.

1 Introduction

It is well-known that the light curves of the long period radially pulsating variable stars show cycle-to-cycle (C2C) variations (e.g. Sterken *et al.* 1999; Young *et al.* 2000; Derekas *et al.* 2012; Evans *et al.* 2015; Plachy *et al.* 2017). From time to time it emerges that RR Lyrae stars are also pulsating as not perfect clocks but their earth-based data are not suitable for investigating such an effect. The *Kepler* space telescope's $\sim$ 1 min sampled short cadence (SC) data, however, seem to be appropriate for such a study. Therefore we analyzed the non-Blazhko RRab sample (19 stars) of the original *Kepler* field. The complete study will be published elsewhere, here only its main results are presented.

2 Cycle-to-cycle variation

Up to a certain magnitude limit ($K_{\rm p} \sim 16$ mag) we detected significant C2C light curve variations for all stars. (For fainter stars, the larger observation scatter prevents the detection.) The most specific difference between the consecutive pulsation cycles is the amplitude difference of the maxima.

We illustrate this finding with Fig. 1 where we plotted three consecutive cycles of NR Lyr folded to one epoch. We can follow that all the maxima are well-covered by observations and differ from each other significantly. The difference between maxima of the cycle 'B' (red pluses) and 'C' (green x symbols) is 1500 $\mathrm{e^{-}s^{-1}}$ (in magnitude scale $K_{\rm p} \sim 0.008$ mag) which is much larger than the observational error of the individual data points (2×10^{-5} mag). The features of the C2C variations of NR Lyr is typical for the entire sample: that is (i) the difference of maxima are generally larger than the difference of other parts of the light curves. (ii) The maxima (and minima) value variation seems to be random but in certain cases a small amplitude cycle followed by a large amplitude one and vice versa which resulted in a period doubled like light curve.

Are this C2C variations instrumental/data handling or intrinsic physical in origin? To answer this questions we tested our data handling and different instrumental effects as potential sources of the C2C variations.

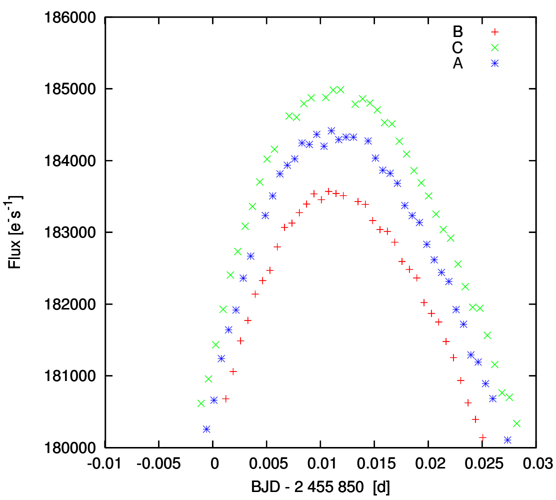

Figure 1: Cycle-to-cycle variations of the SC flux curve of NR Lyr. Three consecutive cycles 'A', 'B' and 'C' folded to the epoch of the cycle 'B'.

2.1 Data handling origin?

The local instrumental trends was handled three different ways. We applied either (i) our moving average subtraction method described in Benkő *et al.* (2014) or (ii) a method in which we adjusted each pulsation cycle to a common zero point. Moreover, (iii) since some stars show no evident trends, their flux curves were also investigated without any further processings. The outputs of these two (or three) data handling methods show qualitatively similar C2C variations which rules out their data handling origin.

2.2 Photometric problems?

We also looked for the source of the differences of the maxima in the pixel maps. We selected high and low maxima pairs from the light curves and plotted the flux in the pixel maps either at the high maxima phase or the flux differences between the high and low maxima phases. Theses figures show that (i) the amplitude difference is connected

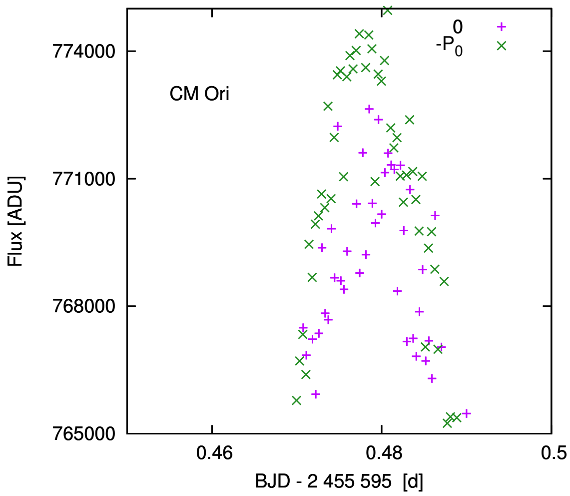

Figure 2: The amplitude difference of two consecutive cycles in CoRoT non-Blazhko star CM Ori. The purple plus signs mean the original light curve points while the green 'x' symbols show the light curve points shifted one pulsation cycle.

to the target stars and there is no other source of flux, and (ii) the position of the stars are unchanged in the pixel mask. These statements make doubts that any serious photometric problems (e.g. drifts, background sources) were at the origin of the C2C variations.

2.3 Unknown instrumental effects?

A complicated device as a space telescope could always have some hidden technical problems. These can be checked if we analyse observations taken by a different instrument. In our case if the control light curves show the same C2C variation effect, then it can hardly be instrumental in origin.

The only independent instrument which observed high precision time series of non-Blazhko RR Lyrae stars is the *CoRoT* satellite (Baglin *et al.*, 2016). Three non-Blazhko stars (CM Ori, CoRoT 103800818, and BT Ser) were observed with the so-called oversampled mode (32 sec sampling) during the *CoRoT* runs.

Investigating the *CoRoT* light curves as we did for *Kepler* stars' data we found C2C variations for the two brightest stars CM Ori ($r_{\rm CoRoT} = 12.64$ mag) and BT Ser ($r_{\rm CoRoT} = 12.99$ mag). Fig. 2 shows the amplitude variations of CM Ori, as it was shown in Fig. 1. Even thought the scatter is evidently larger for this star than for NR Lyr (Fig. 1) the amplitude variations are obvious. The maximal difference between high and low amplitude maxima is about 0.005-0.006 mag. This value is the same as we estimated for *Kepler* stars.

3 Appearing additional modes

We found high S/N significance additional frequencies in the Fourier spectra of six stars. Two types of such spectra are shown in Fig. 3: (i) The top spectra show clear highly significant frequency patterns containing with the radial second overtone f_2 and its linear combinations: $f_2 - f_0$, $2(f_2 - f_0)$, $2f_0 - f_2$, $3f_0 - f_2$, etc. (ii) The bottom panels illustrate the cases where only one frequency (and may be some linear combinations) appears. The identification of this frequency is either the radial first overtone f_1, or $3f_0 - f_2$ as we saw

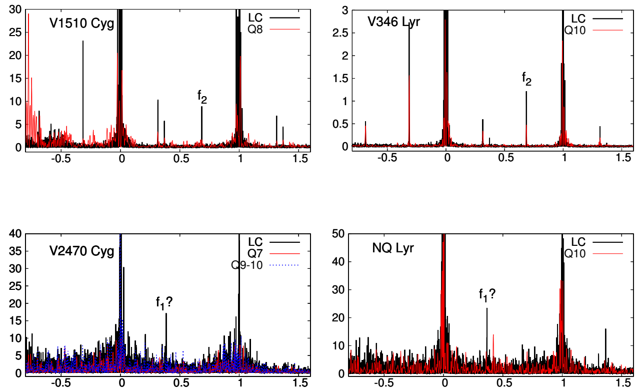

Figure 3: Power spectra of the residual light curves in the frequency range of f_0 and $2f_0$. The black curves show the LC spectra. Spectra computed from the SC data are signed red and blue curves (see also labels in panels). We normalized the frequency scales as $(f - f_0)/f_0$ and the amplitude scales are normalized to the signal to noise ratio of the LC spectra. Significant frequencies are detected close to the positions of the radial overtone modes f_1 or f_2.

in KIC 7257008 (Molnár *et al.*, 2014). In the former case these stars are anomalous RRd stars (Soszyński *et al.*, 2016) with extremely low frequency ratio ($f_0/f_1 < 0.735$). In both (i) and (ii) cases the extra frequencies show temporal amplitude variations and some frequency variations are also presented. We mention, that we have not detected significant half-integer frequencies at the position of $3/2 f_0$ which are the highest amplitude frequency of the period doubling phenomenon of the Blazhko stars.

4 Blazhko effect?

To check the non-Blazhko nature of the sample stars we investigated the pre-whitened Fourier spectra of the long cadence (LC) data around the main pulsation frequencies f_0 (Fig. 4). All the visible side frequencies are coincided an instrumentral frequency connected with the *Kepler* year ($P_{\rm K} = 372.57$ d) as $f_0 \pm k f_{\rm K}$, where $k = 1/2$ or $k = 1, 2, \ldots$ and $f_{\rm K} = 1/P_{\rm K}$ d^{-1}. The detailed investigations showed that the differences between the calculated instrumental frequencies and the observed ones are within the Rayleigh frequency resolution except the case of V346 Lyr. That is, V346 Lyr might be a Blazhko star with the period of 38.33 d which is close to the period of $0.1P_{\rm K}$.

We tested the frequency modulation part of the potential Blazhko effects separately by using the O−C diagrams. Some of the Fourier spectra of these diagrams show significant frequencies, however, these frequencies are always equal to one of the frequency calculated from the side peaks around the harmonics in Fig. 4. In other words, no additinal well-settled Blazhko candidates has been found, These findings strengthened the non-Blazhko nature of most of the sample stars and seems to contradict the extremely large (>90%) Blazhko occurence obtained form *K2* RR Lyrae stars by Kovács (2018).

5 Conclusions

Our main findings on the *Kepler* non-Blazhko stars are the followings:

- (1) Up to a given brightness limit all stars show C2C light curve variations.

- (2) At least one third of the sample show permanently excited extra modes, and some other stars show such modes excited temporarily.
- (3) Only one star (V346 Lyr) can be classified as a Blazhko star with high probability which means two important things: (i) the C2C variation phenomenon is independent from the Blazhko effect and (ii) the Blazhko incidence ratio is still around 50%.

In the case of formerly studied regular C2C light curve variations of the Blazhko stars as period doubling (Kolenberg *et al.*, 2010; Szabó *et al.*, 2010) or other resonances (Molnár *et al.*, 2012, 2014) suggest that the extra modes which manifest additional frequencies in the Fourier spectra, can cause regular C2C variations of the light curves. Plachy *et al.* (2013) found chaotic solutions in the Florida-Budapest hydrocode and these model light curves show small amplitude non-repetitive (chaotic) variations where the C2C maxima changes are the strongest similarly to our observations. The spectra of the model light curves also contains additional small amplitude frequencies, however, these frequencies are in subharmonic positions (e.g. $f_0/2$, $3f_0/4$) and we did not detect such frequencies. In the present situation it is not clear whether these C2C variations are connected to the pulsation or they are rather atmospheric effects.

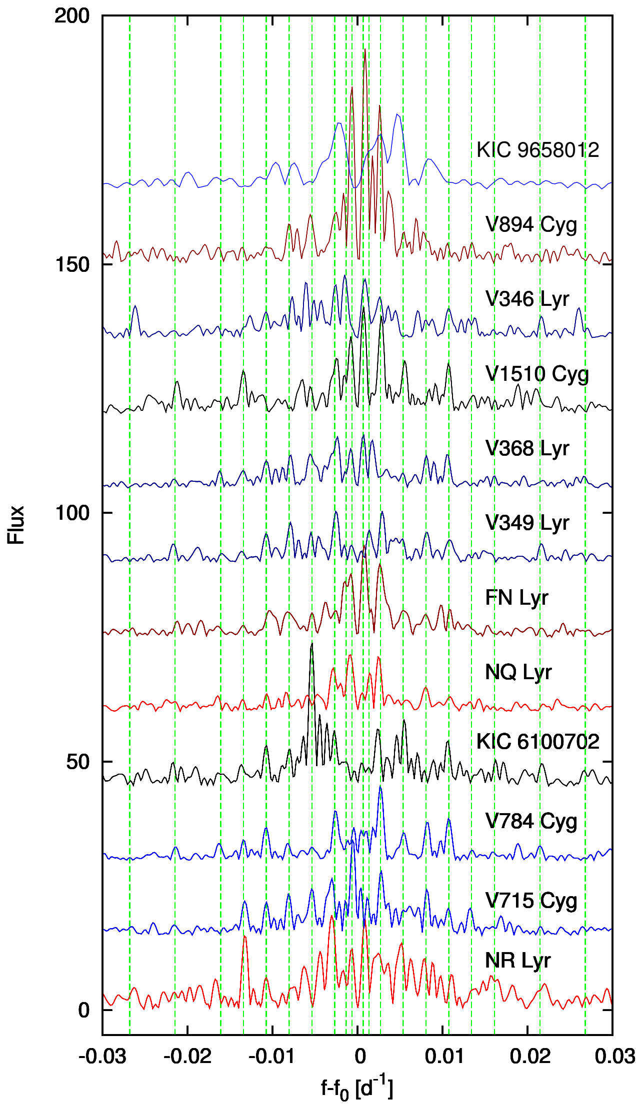

Figure 4: Pre-whitened Fourier spectra of some sample stars around the main pulsation frequency f_0. Green vertical lines show the position of the instrumental frequencies $f_K/2$, $f_K/4$, and kf_K, $k = 1, 2, \ldots, 9$. For better visibility each spectum is consecutively shifted vertically by 15. The different flux scales of different stars are re-scaled by subtracting or dividing them with a small number (2,3, or 4). The similarly scaled curves have the same color.

Acknowledgments

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