THE BLAZHKO EFFECT AND ADDITIONAL EXCITED MODES IN RR LYRAE STARS

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ABSTRACT

Recent photometric space missions, such as CoRoT and *Kepler* revealed that many RR Lyrae stars pulsate – beyond their main radial pulsation mode – in low amplitude modes. Space data seem to indicate a clear trend, namely overtone (RRc) stars and modulated fundamental (RRab) RR Lyrae stars ubiquitously show additional modes, while non-Blazhko RRab stars never do. Two *Kepler* stars (V350 Lyr and KIC 7021124), however, apparently seemed to break this rule: they were classified as non-Blazhko RRab stars showing additional modes. We processed *Kepler* pixel photometric data of these stars. We detected small amplitude, but significant Blazhko effect for both stars by using the resulted light curves and O−C diagrams. This finding strengthens the apparent connection between the Blazhko effect and the excitation of additional modes. In addition, it yields a potential tool for detecting Blazhko stars through the additional frequency patterns even if we have only short but accurate time series observations. V350 Lyr shows the smallest amplitude multiperiodic Blazhko effect ever detected.

Keywords: stars: oscillations — stars: variables: RR Lyrae — techniques: photometric — space vehicles

1. INTRODUCTION

During the past decades RR Lyrae stars were regarded as useful tools for measuring cosmic distances, but otherwise rather boring stars. They pulsate radially, and the mechanism of this pulsation assumed to be well-known. A few phenomena, however, challenges this simplistic view. One of them is the Blazhko effect (Blazhko 1907), a periodic amplitude and/or phase variation of the light curves which is shown by about 50 percent of the RRab stars and there is no generally accepted physical explanation (see e.g Szabó 2014 for a present review).

The interest in RR Lyrae stars has been dramatically increased through the discoveries of photometric space missions CoRoT (Baglin et al. 2006) and *Kepler* (Borucki et al. 2010). These objects are either characterized by completely new phenomena, like period-doubling (Kolenberg et al. 2010; Szabó et al. 2010) and low amplitude (potentially non-radial) pulsations (Chadid et al. 2010; Benkő et al. 2010), or phenomena which proved to be more frequent in the space-based data compared with the ground-based ones, such as multiperiodic or irregular Blazhko effects (Guggenberger et al. 2012; Benkő et al. 2014).

The observation of AQ Leo by the MOST satellite (Gruberbauer et al. 2007) was the first detailed photometric spaceborne observation which was taken on an RR Lyrae star. AQ Leo is a double-mode pulsating (RRd) star: it pulsates in its fundamental and first radial overtone mode simultaneously. The frequency analysis of AQ Leo showed that its Fourier spectrum contains an additional frequency and its harmonic beyond the expected frequencies of the two radial modes and their linear combinations. After analyzing the CoRoT and *Kepler* data it turned out that all RRc and RRd stars exhibit such extra modes (Chadid 2012; Szabó et al. 2014; Moskalik et al. 2015). A common property of these additional modes is

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their period ratios with the radial overtone periods which is about 0.61-0.62. The proximity of these numbers to the reciprocal of the famous golden ratio (1.618033...) inspired interesting speculations (Linder et al. 2015) about the pulsation dynamics. Lately these additional modes have been found in ground-based data, as well (Jurcsik et al. 2015), what is more, a new group has been identified, where the period ratio is about 0.686 instead of 0.618 (Netzel et al. 2014).

Interestingly, these frequencies have never been detected in any RRab stars, but other low amplitude additional frequencies do appear. Some of them are the half-integer frequencies (HIFs = $1/2f_0$, $3/2f_0$, ...,), where f_0 is the frequency of the radial fundamental mode. These are connected to the period doubling effect. The mostly accepted explanation of this effect is a 9:2 resonance between the fundamental and the 9th radial overtone, a so-called strange mode (Kolláth, Molnár & Szabó 2011). The physical resonance destabilizes the fundamental fixed point corresponding to the fundamental mode, giving rise to a period doubled dynamical state characterized by alternating maxima and minima in the light curve, and HIFs in the Fourier spectra. Other low amplitude additional frequencies seem to be related to the first (f_1) or second (f_2) radial overtones (Benkő et al. 2010). Some theoretical model computations confirmed the possibility of triple resonance states where the fundamental, the first overtone and a strange modes are exited simultaneously (Molnár et al. 2012). Other resonance combinations (e.g. fundamental and second overtone; fundamental, first, and second overtone together; etc.) which are detected in real stars, have not been modelled yet.

In the model calculations the appearance of the additional modes are independent from the Blazhko effect, but observations suggest a strong correlation. By unifying the published CoRoT and *Kepler* Blazhko RRab samples (Kolenberg et al. 2011; Szabó et al. 2014; Benkő

et al. 2014) we get 22 stars and among them 17 (77%) show additional frequencies. If we do the same comparison for non-Blazhko stars (Nemec et al. 2011, 2013; Szabó et al. 2014) we find 2 stars (V350 Lyr and KIC 7021124) among 25 (8%) which pulsate in additional modes, as well.

This paper focuses on these two objects, demonstrating that they are not exceptions in the sense they do show the Blazhko effect, albeit with very small amplitude.

2. DATA

We present and analyze those two stars (V350 Lyr and KIC 7021124), where additional small amplitude modes were discovered, but the Blazhko effect has not been detected previously. Up to now more than a thousand papers based on *Kepler* data have been published, so the basic features of the mission are widely known. We refer to Koch et al. (2010) and Jenkins et al. (2010a,b) for detailed description of the main characteristics of the telescope and the data. All the technical details are published in the following handbooks: Van Cleve et al. (2009); Fanelli et al. (2011); Jenkins et al. (2013).

The *Kepler* photometry of the non-Blazhko RR Lyrae stars was studied first by Nemec et al. (2011) on the basis of the commissioning phase and the first five quarters (Q0-Q5). Furthermore, Nemec et al. (2013), along with the ground-based spectroscopic observations, also published new results from the *Kepler* photometry of the quarters Q0-Q11. The present paper uses the complete (Q0-Q17) long cadence (LC) *Kepler* observations.

The *Kepler* data are publicly available[1] in two forms: light curve (SAP, PDC) and target pixel files. The pixel data require more work to extract precise photometry, but for RR Lyrae stars which have relatively large amplitudes the pixel data should be more reliable (Benkő et al. 2014).

Briefly, the predefined apertures of the light curve data are in many cases too small (that is, they contain too few pixels), so some fraction of the stellar flux is lost. This flux loss is typically time dependent and can cause instrumental trends and amplitude changes. To minimize such effects, we processed the pixel data of the non-Blazhko RR Lyrae stars in the same manner as we did for the Blazhko stars: (1) we defined a tailor-made aperture for each star and observing quarter, then (2) we extracted the flux. (3) The flux data of the different quarters of a star were stitched together by scaling and/or shifting. (4) Finally, we removed the likely instrumental trends and transformed the flux values to the magnitude scale. The interested reader is referred to Benkő et al. (2014) for details. Tables 1 and 2 show excerpts from the processed data files as an example[2]. Both former studies of non-modulated *Kepler* RR Lyrae stars (Nemec et al. 2011, 2013) used the *Kepler* light curves. This letter is the first, where the pixel data of non-Blazhko stars are used.

3. ANALYSIS AND RESULTS

Our main tools are the Fourier analysis realized by the MUFRAN program package (Kolláth 1990) and the 'observed minus calculated' (O−C) diagram method (see

[1] via MAST: https://archive.stsci.edu/kepler/data_search/search.php
[2] All rectified light curves are available at http://www.konkoly.hu/KIK/data.html.
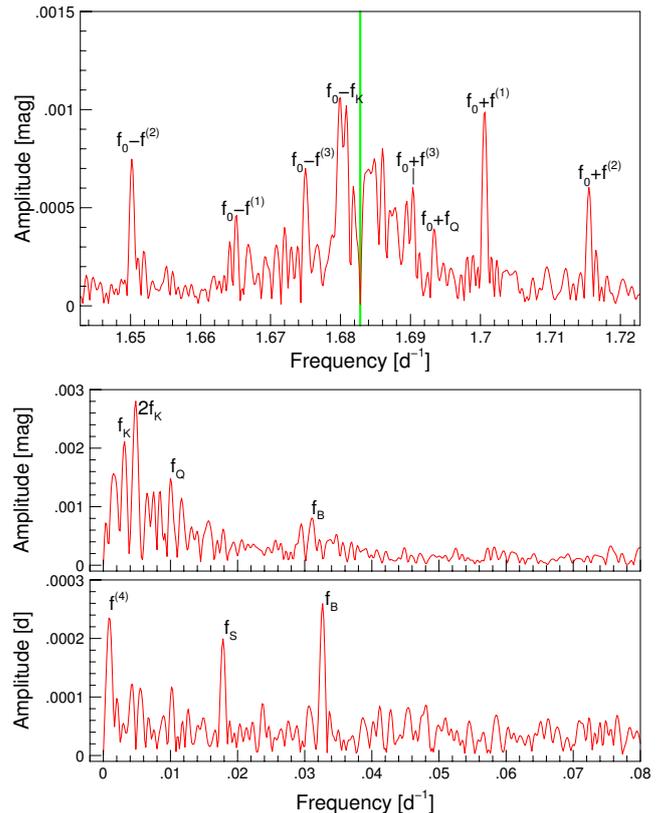

Figure 1. Side peaks around the main pulsation frequency of V350 Lyr after a pre-whitening step (top). The green vertical line shows the position of the pre-whitened main pulsation frequency f_0. Low frequency range of the Fourier spectra of V350 Lyr light curve (middle) and O−C diagram (bottom). See text for more details.

e.g. Sterken 2005). The O−C diagram is calculated from the maxima time of the light curve. The details of the analysis are summarized in Benkő et al. (2014). Throughout this paper the numerical values (frequencies, amplitudes, etc.) are written with the significant number of digits plus one digit.

3.1. *V350 Lyr = KIC 9508655*

The observational history of this star is rather short. Hoffmeister (1966) discovered and classified it as an RR Lyrae variable star, giving two maximum times. Galkina & Shugarov (1985) determined some basic photometric parameters (epoch, period, maximum, minimum values, and amplitude) from their photographic observations. They assumed a period variation on longer time scale, because they could not find a common period for their maxima and Hoffmeister's ones.

After a long hiatus, *Kepler* entered the scene. V350 Lyr was classified by Benkő et al. (2010) as a non-Blazhko star on the basis of 138 d (Q1-Q2) *Kepler* observations though the possibility of a small amplitude Blazhko effect below the detection limit was also noted, because the residual spectrum after pre-whitening with the main pulsation frequency $f_0 = 1.682814$ d^{-1} and its harmonics, showed a bunch of small amplitude peaks around each pre-whitened frequency. An additional frequency at $f = 2.84019$ d^{-1} and its linear combination with the main pulsation frequency was detected as the most interesting feature of this star. At that time V350 Lyr was

Table 1
Sample from the rectified data file of V350 Lyr

No	Time (BJD−2454833)	Flux (e⁻s⁻¹)	Zero point shift (e⁻s⁻¹)	Scaling factor	Corrected flux (e⁻s⁻¹)	Corrected K_p (mag)
1	131.51274	5431.0	0.00	1.073	5241.81728032	0.20251409
2	131.53318	5381.9	0.00	1.073	5192.71476411	0.21273262
3	131.55361	5333.2	0.00	1.073	5144.01224792	0.22296381
4	131.57405	5279.5	0.00	1.073	5090.30973174	0.23435827
5	131.59448	5185.8	0.00	1.073	4996.60721555	0.25453076
...	...	...	...	...	...	...

Note. — The first five data lines from the file of V350 Lyr (`table_kplr009508655.tailor-made.dat`). The columns contain serial numbers, baricentric Julian dates, flux extracted from the tailor-made aperture, zero point shifts (0.0 = no shifting), scaling factors (1.0 = no scaling), stitched (shifted, scaled and trend filtered) flux and their transformation into the K_p magnitude scale, respectively. See the text for the details.

Table 2
Sample from the rectified data file of KIC 7021124

No	Time (BJD−2454833)	Flux (e⁻s⁻¹)	Zero point shift (e⁻s⁻¹)	Scaling factor	Corrected flux (e⁻s⁻¹)	Corrected K_p (mag)
1	131.51264	19185.6	500.00	0.946	14954.71597491	−0.16944681
2	131.53307	18645.9	500.00	0.946	14415.00956331	−0.12953873
3	131.55351	18174.7	500.00	0.946	13943.80315174	−0.09345450
4	131.57394	17738.7	500.00	0.946	13507.79674020	−0.05896268
5	131.59437	17377.8	500.00	0.946	13146.89032863	−0.02955899
...	...	...	...	...	...	...

Note. — The first five data lines from the file of KIC 7021124 (`table_kplr007021124.tailor-made.dat`). The meaning of the columns are the same as in Table 1.
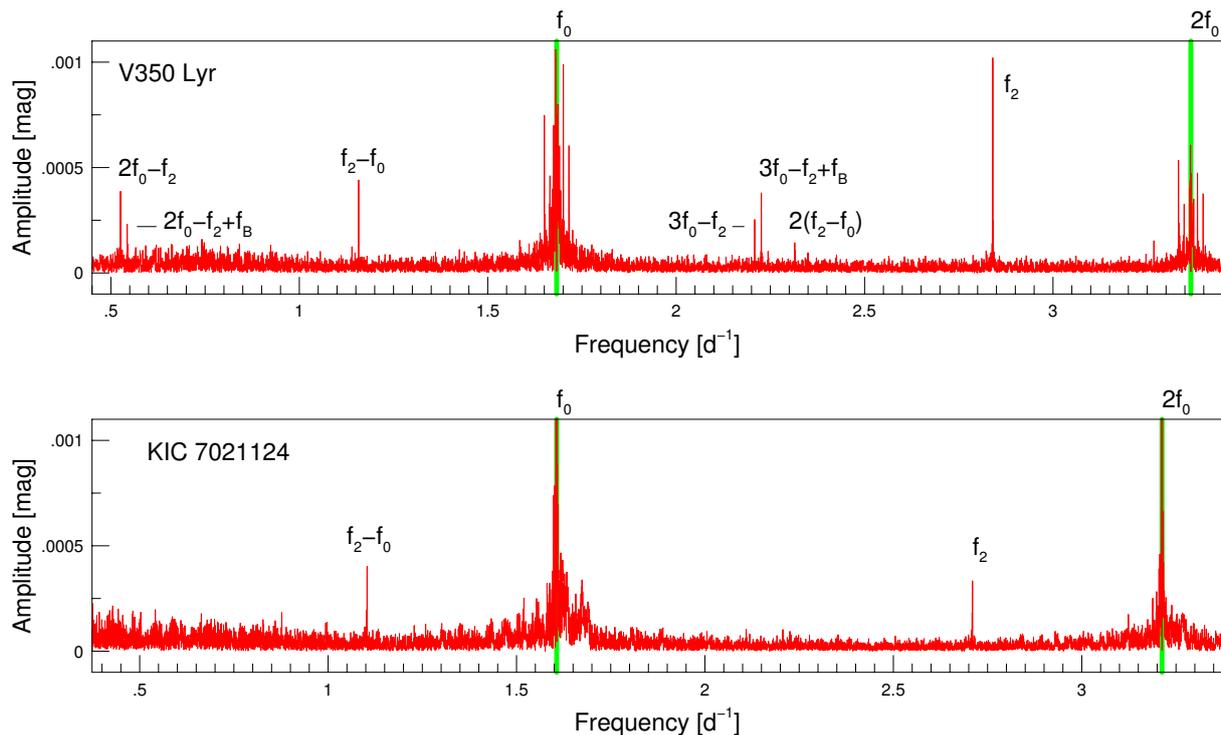

Figure 2. Additional peak identifications in the the pre-whitened Fourier spectrum of V350 Lyr (top) and KIC 7021124 (bottom) light curves. The green vertical lines show the positions of the pre-whitened frequencies f_0 and $2f_0$.

though to be the first and the only example for a non-Blazhko RRab star pulsating in an additional mode. The frequency was identified with the second radial overtone $f = f_2$. Nemec et al. (2011) confirmed both findings (non-Blazhko behavior and the excited additional mode) using the *Kepler* light curve data from Q1-Q5. In the following we demonstrate that in contrast with earlier results based on shorter *Kepler* data, V350 Lyr is indeed a Blazhko-modulated star.

To do this, now we turn to the analysis of the latest available *Kepler* data. The Fourier spectrum of the rectified light curve based on Q1-Q17 pixel data is dominated

by the main pulsation frequency ($f_0 = 1.682828$ d^{-1}) and its harmonics (kf_0, $k = 1, 2, \ldots$,). Thirteen harmonics can be detected up to the Nyquist frequency (24.5 d^{-1}). By pre-whitening the light curve with these dominant frequencies, we found multiplet structures around their positions (top panel in Fig. 1): $kf_0 \pm f^{(i)}$, where $k = 1, 2, \ldots$, and $i = 1, 2$ or 3. Assuming that these multiplets are combinations of some modulation side peaks, we can calculate the individual modulation frequencies. The averaged differences of the $f^{(i)}$ frequencies from the two side peaks around f_0 are $f^{(1)} = 0.01773$ d^{-1}, $f^{(2)} = 0.03265$ d^{-1}, and $f^{(3)} = 0.00772$ d^{-1}, respectively. Many stars in our sample show a frequency around 0.008 d^{-1}, so these frequencies together with $f^{(3)}$ must be of instrumental origin. Some additional instrumental peaks (e.g. $f_0 - f_K$, $f_0 + f_Q$, see Fig. 1) are also detectable. Here we define the frequencies belonging to the *Kepler* year as $f_K = 1/372.5$ d^{-1} and to average the quarter as $f_Q \approx 1/90$ d^{-1}. We introduce the notation $f^{(2)} = f_B$ and $f^{(1)} = f_S$ for the intrinsic modulations, the primary and secondary Blazhko frequencies, respectively.

It is noticeable, that f_B and f_S are nearly harmonics: $f_B \approx 2f_S$. However, the difference between the exact harmonic and the actual value ($2f_S - f_B = 0.0028$) is significantly higher than the Rayleigh frequency resolution (≈ 0.0007 d^{-1}). This means that we are facing a multiperiodic Blazhko modulation with nearly resonant frequencies similar to CZ Lac, RZ Lyr (Sódor et al. 2011; Jurcsik et al. 2012) and numerous cases in the *Kepler* Blazhko sample (Benkő et al. 2014).

The low frequency range of the Fourier spectrum (middle panel in Fig. 1) is dominated by the technical peaks, but f_B ($A^{AM}(f_B) = 0.8$ mmag)[3] can also be detected. The peak at f_S, however, is not significant ($A^{AM}(f_S) = 0.6$ mmag). The highest peak between the harmonics is $f_2 = 2.840182$ d^{-1} (top panel in Fig. 2). We also detect numerous linear combination frequencies (such as 1.157383 d$^{-1} = f_2 - f_0$, 0.525460 d$^{-1} = 2f_0 - f_2$, $2.314693 = 2(f_2 - f_0)$, etc.). The Fourier spectrum features clearly demonstrate that V350 Lyr is a typical Blazhko RR Lyrae star. Nevertheless, the LC light curve does not show evident modulation. The rms of the non-linear fit using the main frequency and its harmonics is 0.0062 mag. This value is 0.0048 mag for the non-modulated V1107 Cyg which has the closest brightness and period parameters to V350 Lyr in the *Kepler* RR Lyr sample. This small difference might be explained by the effect of the additional frequencies of V350 Lyr.

To clarify the situation we prepared the O−C diagram, that tests the frequency modulation part of the potential Blazhko effect. The O−C diagram itself does not show evident modulation, however, its Fourier spectrum (bottom panel in Fig. 1) contains three significant frequencies: f_B, f_S, and a third one at $f^{(4)} = 0.000861$ d^{-1} with the amplitudes of $A^{FM}(f_B) = 0.0003$ d, $A^{FM}(f_S) = 0.0002$ d, and $A(f^{(4)}) = 0.0003$ d, respectively. The latter frequency belongs to a long period variation ($P^{(4)} \approx 3.1$ years) which has no signs in the light curve or the
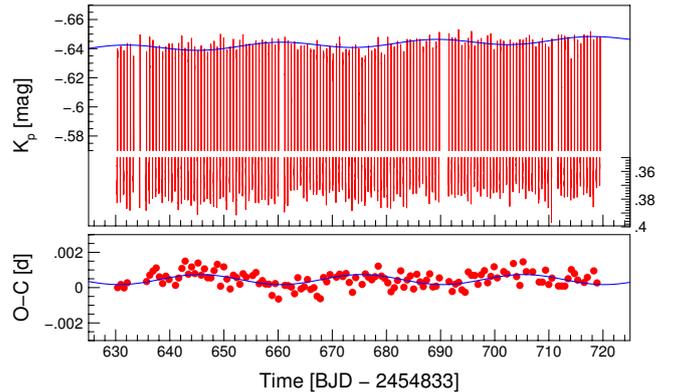
Figure 3. (top) Short cadence (SC) light curve of V350 Lyr from Q7. For clarity the middle values of the light curve are not plotted here, just the two extrema (minima and maxima). (bottom) O−C diagram of the SC light curve above. The continuous blue lines show the best fit sinusoid of the parameters $P_B = 28.7$ d, $A = 0.0025$ mag (for maxima) and $P_B = 29.9$ d, $A^{FM}(f_B) = 0.00028$ d (for O−C values).

light curve spectrum. At the same time $f^{(3)}$ can not be detected here in the O−C spectrum, which supports its technical origin.

V350 Lyr was observed in SC mode in Q7 and for one month in Q11.3. These observations give us an additional opportunity to check the Blazhko nature of this star. We processed the SC pixel data exactly the same way as we did the LC data. The SC light curve indeed shows slight amplitude changes (top panel in Fig. 3). The magnitude of this variation is less than 0.005 mag. The O−C diagram of the SC data (bottom panel in Fig. 3) shows expressed variation with a period of 30 days which can be identified with the Blazhko period P_B.

We conclude that V350 Lyr is a Blazhko star showing (at least) two modulations with small variation amplitude and frequency, and these two modulation frequencies are in nearly 1:2 resonance. The O−C diagram shows $f^{(4)} = 0.000861$ d^{-1} beyond the two Blazhko frequencies. This frequency could either belong to (1) a third Blazhko modulation or (2) is the consequence of the light-time effect caused by a gravitational bound companion. Such O−C diagrams were studied by and Hajdu et al. (2015) and Guggenberger & Steixner (2014) in the case of RR Lyrae stars, recently. (3) Less likely: of instrumental origin.

3.2. *KIC 7021124*

The additional mode of KIC 7021124 was discovered by Nemec et al. (2011) making this star the second non-Blazhko star showing additional mode at that time. Nemec et al. (2011) found this star to be very similar to V350 Lyr in many aspects (e.g. mass, luminosity, Fourier parameters). At that time only Q1 data were available. Here we deprive this star of this privileged status, as well.

Using the entire data set from Q1 to Q17 we do not find significant amplitude modulation. The pre-whitened spectrum does not show distinct side peaks around the harmonics of the main pulsation period $f_0 = 1.606474$ d^{-1} and the significant peaks in the low frequency range are presumably technical. The spectrum contains an additional frequency $f_2 = 2.70999$ d^{-1} (see bottom panel in Fig. 2) and some of its linear combina-
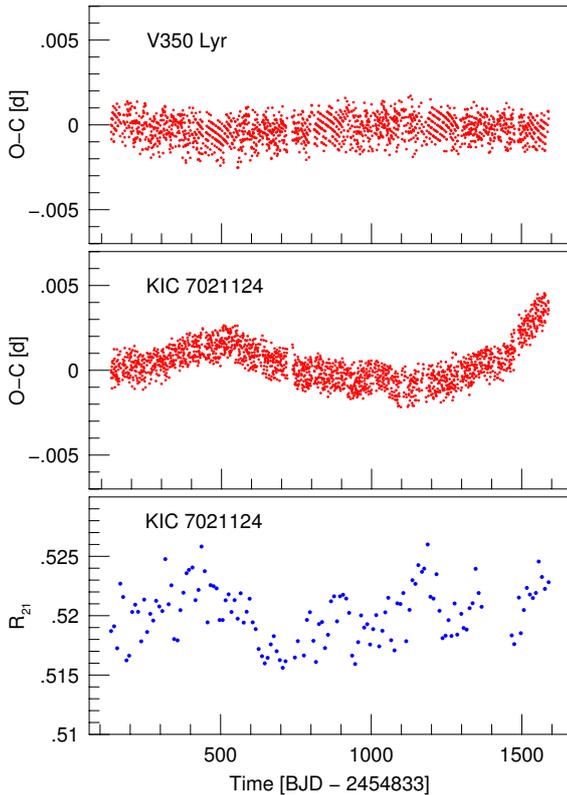
Figure 4. O−C diagrams of V350 Lyr (top). O−C diagrams of KIC 7021124 (middle) and the time dependence of its amplitude ratio R_{21} (bottom).

tion (e.g. $f_2 - f_0$), but generally it is more simple than the spectrum of V350 Lyr.

The O−C diagram, however, shows a clear period change (middle panel in Fig. 4). The shape of the O−C curve is close to, but not strictly sinusoidal. In the Fourier spectrum of this O−C diagram there are two significant peaks at $f^{(5)} = 0.00087$ d^{-1}, $(A(f^{(5)}) = 0.0011$ d) and at $2f^{(5)} = 0.0019$ d^{-1}, $(A(2f^{(5)}) = 0.0005$ d). Further peaks can not be detected in the higher frequency range. These frequencies yield a rough period estimation of around ~ 1400 d, since the variation period – if it is periodic at all – is comparable to the total observing time. The appearance of the overtone indicates the non strictly sinusoidal nature of the variation. The similar period of $f^{(4)}$ and $f^{(5)}$ raises the possibility that these variations result from instrumental effects. Some facts contradict such a scenario. (1) It is highly unlikely that there are problems with the time measurements of *Kepler*. (2) The amplitude $A(f^{(5)}) = 0.0011$ d=1.55 min is much higher than that of the longest period of V350 Lyr $(A(f^{(4)}) = 0.0003$ d=0.4 min). (3) The phase of these two similar time-scale variations are also different (cf. top and middle panels in Fig. 4). All in all, both variations described by $f^{(4)}$ and $f^{(5)}$ seem to be real. The question of their nature however, remains.

In the case of V350 Lyr we have already mentioned some possible scenarios. The frequency modulation due to a long period Blazhko effect would be an adequate explanation for KIC 7021124 as well, because

Blazhko cycles of long characteristic time scales are known (Soszyński et al. 2011). The only problem is the lack of the amplitude modulation. It is known, however, that if we characterize the light curve with the Fourier parameters defined by Simon & Teays (1982), the amplitude ratio $R_{21} = A(2f_0)/A(f_0)$ is very sensitive to the amplitude changes and is highly unaffected by technical problems. The bottom panel of Fig. 4 shows the variation of R_{21} in time. The diagram was constructed with the PERIOD04 program (Lenz & Breger 2005). The R_{21} parameter shows a long-term variation, very similar to that of the O−C values. The phase of the long time-scale variation is correlated with the O−C diagram.

Simultaneous amplitude and frequency variation constitutes a strong evidence for the presence of the Blazhko effect in this object. Its small amplitude and long cycle prevented its detection until now.

4. CONCLUSIONS

We extracted and presented the time series of two RR Lyrae stars (V350 Lyr and KIC 7021124) – which were formerly known as un-modulated ones showing additional excited small amplitude periodicites. We used the *Kepler* pixel data and our tailor-made apertures to minimize flux loss. The flux curves were scaled, shifted and de-trended in the same way as was done for the Blazhko stars (Benkő et al. 2014).

The study of these two stars resulted in evidence for the Blazhko behavior in both cases. In the case of V350 Lyr we demonstrated that this star shows simultaneous amplitude and frequency modulations with two small amplitude frequencies with nearly 1:2 ratio. KIC 7021124 is also a Blazhko star with extremely low amplitude modulation at about the *Kepler* detection limit, featuring a significant long-period frequency modulation.

The smallest known Blazhko AM amplitude so far has been 0.6 mmag for V838 Cyg (Nemec et al. 2013). The secondary AM modulation amplitude of V350 Lyr has the same amplitude, however, this object shows multiple modulations with the smallest amplitude components (0.6 and 0.8 mmag) ever found.

KIC 7021124 is also a record holder: it has by far the longest Blazhko period with such a small amplitude. A possible trend was reported between the Blazhko period and the amplitude of the AM parts of the effect (see in Fig. 9 in Benkő et al. 2014). KIC 7021124 seems to diverge from this trend. This points out that the trend might partially be a sampling effect: long period and small amplitude modulations can hardly be detected even from space.

We mention that these two stars are the most metal poor stars in the *Kepler* Blazhko sample: V350 Lyr has [Fe/H]=−1.83 dex, and KIC 7021124 has [Fe/H]=−2.18 dex (Nemec et al. 2013). The more metal poor RR Lyrae stars in the sample (NR Lyr, FN Lyr, NQ Lyr) are all non-Blazhko stars. Is the amplitude of the AM part of the Blazhko effect related to the metallicity? A direct metallicity – AM amplitude relation can be ruled out because e.g. V838 Cyg has also small AM amplitude but it is the most metal rich ([Fe/H]=−1.01 dex) among the *Kepler* Blazhko stars. If we complement the *Kepler* Blazhko sample with V350 Lyr and KIC 7021124 we find that the metallicities of the non-Blazhko stars distribute over a wider range

(between -2.54 and -0.05 dex) than that of the Blazhko stars (-2.18 and -1.01). What is even more interesting: both the extremely metal rich and metal poor Blazhko stars exhibit extremely low AM amplitude.

On the basis of the CoRoT and *Kepler* Blazhko samples – and since both objects studied here proved to be Blazhko stars – we can provide a *strict rule for RRab stars: the additional modes appear only in the presence of the Blazhko effect.* In this case we were able to deduce the Blazhko nature for those stars where the Blazhko cycle is long (much longer than the observed time span), but some excited additional modes are evident. This situation will be common in the relatively short observing runs of K2 (Howell et al. 2014) and TESS (Ricker et al. 2015).

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