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 that, 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 a small amplitude (but significant) Blazhko effect for both stars by using the resulting 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.

Key words: space vehicles – stars: oscillations – stars: variables: RR Lyrae – techniques: photometric

Supporting material: machine-readable tables

1. INTRODUCTION
In recent decades, RR Lyrae stars have been regarded as useful tools for measuring cosmic distances, but otherwise are rather boring stars. They pulsate radially, and the mechanism of this pulsation is assumed to be well known. A few phenomena, however, challenge this simplistic view. One of them is the pulsation is assumed to be well known. A few phenomena, rather boring stars. They pulsate radially, and the mechanism of the RRab stars, and there is no generally accepted physical explanation (see, e.g., Szabó 2014 for a recent review).

The interest in RR Lyrae stars has 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 (Benkő et al. 2010; Chadid et al. 2010), or phenomena that 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 Microvariability and Oscillations of Stars satellite (Gruberbauer et al. 2007) was the first detailed photometric spaceborne observation that 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 their period ratios with the radial overtone periods that are 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 pulsation dynamics. Lately, these additional modes also have been found in ground-based data (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 additional low-amplitude frequencies do appear. Some of them are the half-integer frequencies (HIFs = 1/2\( f_0 \), 3/2\( f_0 \), ..., 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 ninth radial overtone, a so-called strange mode (Kolláth et al. 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 mode are excited simultaneously (Molnár et al. 2012). Other resonance combinations (e.g., fundamental and second overtone; fundamental, first, and second overtone together; etc.) that are detected in real stars have not been modeled yet.

In the model calculations, the appearance of the additional modes is 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; Benkő et al. 2014; Szabó 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%) that pulsate in additional modes as well.

This Letter focuses on these two objects, demonstrating that they are not exceptions in the sense that 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, 2010b) for detailed descriptions of the main characteristics of the telescope and the data. All of the technical details are published in the following handbooks: Van Cleve et al. (2009), Fanelli et al. (2011), and 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 quarters Q0–Q11. The present Letter uses the complete (Q0–Q17) long-cadence (LC) Kepler observations.

The Kepler data are publicly available² 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 that 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, and (2) then 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 study 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, e.g., Stetson 2005). The O–C diagram is calculated from the maxima 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 and minimum values, and amplitude) from their photographic observations. They assumed a period variation on a longer timescale because they could not find a common period for their and Hoffmeister’s maxima.

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 day (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 were detected as the most interesting features of this star. At that time, V350 Lyr was thought to be the first and only example of 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 to 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.

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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.
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 Figure 1): \(k f_0 \pm f^i\), where \(k = 1, 2, \ldots\), and \(i = 1, 2, 3\). 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 \(f^{(3)} = 0.0077\) 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., \(f_0 - f_{0K}\), \(f_0 + f_{0}\); see Figure 1) are also detectable. Here, we define the frequencies belonging to the Kepler year as \(f_K = 1/372.5\) d\(^{-1}\) and to the average of the quarter as \(f_0 \approx 1/90\) d\(^{-1}\). We introduce the notations \(f^{(2)} = f_{0K}\) and \(f^{(1)} = f_{0}\) for the intrinsic modulations, the primary and secondary Blazhko frequencies, respectively.

It is noticeable that \(f_{0K}\) and \(f_{0}\) are nearly harmonic: \(f_{0K} \approx 2f_{0}\). However, the difference between the exact harmonic and the actual value (2\(f_{0} - f_{0K}\) = 0.0028) is significantly higher than the Rayleigh frequency resolution (\(\approx 0.0007\) d\(^{-1}\)). This means that we are facing a multiperiodic Blazhko modulation with nearly resonant frequencies similar to CZ Lac, RZ Lyr (Sógor 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 Figure 1) is dominated by the technical peaks, but \(f_{0K}\) \((A_{\text{AM}}(f_{0K}) = 0.8\) mmag\(^3\)) can also be detected. The peak at \(f_{0}\), however, is not significant \((A_{\text{AM}}(f_{0}) = 0.6\) mmag\). The highest peak between the harmonics is \(f_2 = 2.840182\) d\(^{-1}\) (top panel in Figure 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 nonlinear 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.

\(^{3}\) From now on, the upper indices AM and FM distinguish the amplitude of the amplitude modulation (AM) and frequency modulation (FM) amplitudes, respectively.

| No. | Time (BJD–2454833) | Flux (e− s\(^{-1}\)) | Zeropoint 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         | 14415.0956331               | -0.12953873           |
| 3   | 131.55351         | 18174.7              | 500.00                        | 0.946         | 13943.8031574               | -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. (This table is available in its entirety in machine-readable form.)
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 Figure 3). The magnitude of this variation is less than 0.005 mag. The O–C diagram of the SC data (bottom panel in Figure 3) shows expressed variation with a period of 30 days that 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 $f^{(3)} = 0.000861 \text{ d}^{-1}$ 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. Recently, such O–C diagrams were studied by Hajdu et al. (2015) and Guggenberger & Steixner (2014) in the case of RR Lyrae stars. (3) Less likely, it is 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 respects (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 $f_0 = 1.606474 \text{ d}^{-1}$, and the significant peaks in the low frequency range are presumably technical. The spectrum contains an additional frequency $f_2 = 2.70999 \text{ d}^{-1}$ (see bottom panel in Figure 2) and some of its linear combination (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 Figure 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 $f^{(5)} = 0.00087 \text{ d}^{-1}$ ($A(f^{(5)}) = 0.0011 \text{ d}$) and at $2f^{(5)} = 0.0019 \text{ d}^{-1}$ ($A(2f^{(5)}) = 0.0005 \text{ d}$). Further peaks cannot be detected in the higher frequency range. These frequencies yield a rough period estimation of around $\sim 1400 \text{ d}$ 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 periods of $f^{(4)}$ and $f^{(5)}$ raise 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 $A(f^{(5)}) = 0.0011 \text{ d}$ is much higher than that of the longest period of V350 Lyr ($A(f^{(4)}) = 0.0003 \text{ d} = 0.4 \text{ minutes}$). (3) The phases of these two similar timescale variations are also different (see top and middle panels in Figure 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 FM due to a long-period Blazhko effect...
would be an adequate explanation for KIC 7021124 as well because Blazhko cycles of long characteristic timescales are known (Soszyński et al. 2011). The only problem is the lack of 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 Figure 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 timescale 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 time series showing additional excited small-amplitude periodicities. 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 FMs with two small-amplitude frequencies with a 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 FM.

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 Figure 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 also has a 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 is that both the extremely metal-rich and metal-poor Blazhko stars exhibit extremely low AM amplitudes.

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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