Extra RR Lyrae Stars in the Original *Kepler* Field of View

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Our previous result from synthetic Galaxy models shows that there are many "hidden" RR Lyrae stars in the original *Kepler* field of view. We were informed about many candidate RR Lyrae stars in this area of the sky by the PlanetHunters community and professional astronomers. We extracted the light curves of these objects, removed the systematic trends, and analyzed the data. The final catalog of these extra RR Lyrae stars contains 23 newly discovered stars. Nearly half of the RRab type stars and one of the new RRc stars show the famous Blazhko modulation. This RRc star is the only modulated RRc star in the *Kepler* field of view. These extra RR Lyrae stars are mostly in the $14 - 17$ magnitude range, which we expect from the Galaxy models. Finally, we discuss the properties of some stars of the new *Kepler* RR Lyrae sample.

1 Modeling the Original *Kepler* Field of View

It is interesting to ask what fraction of the total RR Lyrae (RRL) population remains hidden in the original *Kepler* field of view (FOV). To investigate this question we used the TRILEGAL (Girardi et al., 2005) and Besançon (Robin et al., 2003) synthetic Galaxy models to simulate the expected number of RRL stars in the *Kepler* FOV. All 21 CCD modules were simulated with both Galaxy models; the total field of each module is $4\,\mathrm{deg}^2$.

For some CCD modules the Besancon model could not finish the simulation properly; the list of the simulated stars breaks at some point before it would print out the total number of simulated stars. Therefore we had to split the original $4\,\mathrm{deg}^2$ area into four smaller parts that cover the area of the CCD modules. This method succeeded in modeling all the CCD modules.

After the simulations completed, we selected those stars that lie in the theoretical RRL instability strip (IS). We found some simulated stars that looked like an RRL star by their temperature and luminosity, but it turned out that they are ~ 1 Gyr old binary systems or evolved $2\,\mathrm{M}_\odot$ stars. We removed these "false RRL" stars, which resulted in a final list of simulated RRL stars.

To get an idea of the error in the number of simulated stars we shifted each CCD module by ± 0.5 degrees along right ascension and declination, and we ran the simulations on these areas as well, and analyzed them in the same way as we did in the original FoV. As expected, we got different numbers of simulated stars for each of these shifted fields. We calculated the standard deviation of the numbers of the simulated RRLs in the shifted fields that we considered to be the error of the number of simulated stars in the *Kepler* FoV.

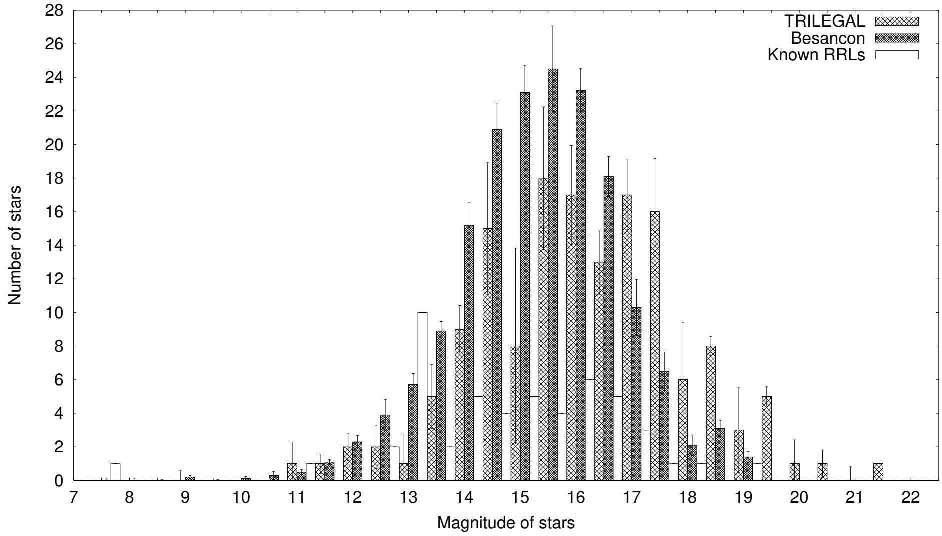

Fig. 1: Dispersion of the simulated and previously known RR Lyrae stars in the original *Kepler* field of view. Different shadings of the histogram represent the results of the simulated number of RRL stars and the known RRL stars as well.

In Fig. 1, we plot the number of simulated RRL stars with respect to their simulated *Kepler*-magnitude for TRILEGAL and Besançon models with the previously known 51 RRL stars in the original *Kepler* FoV. These known RRL stars are collected from (Benkő et al., 2010; Nemec et al., 2011, 2013; Moskalik et al., 2015; Sódor et al., 2017). The histogram shows that the maxima of the two Gaussians are between $15^{\text{th}} - 16^{\text{th}}$ magnitude range where we would expect many more new RRL stars. Similarly, based on the histogram, we expect more RRL stars in the faint magnitude range. Also, we expect no more or very few new RRL stars at the bright end (brighter than 14 magnitude) of Fig. 1.

2 Data Reduction

The *Kepler Input Catalog* (KIC) includes more than 150 000 targets. Around each target, a few pixel wide area was read out with an integration time of 6.02 s. By adding 270 such exposures, we get long cadence (LC) stamps while short cadence (SC) stamps involve adding 9 exposures. A time series of such long/short cadence stamps is called a target-pixel file (TPF).

The main problem with these new RRL stars is that a large fraction of stars are located only a few pixels away from a much brighter star or they are located at the edge of the TPF file; therefore, we can not estimate the amplitudes of the light curves for the following reasons. First, an unknown amount of the flux is outside of the TPF file. Second, we had to extract the light curve of the RRL star using a mask that contains the brighter star as well.

We extracted the flux variation for each pixel of the given star using the PyKE (Still & Barclay, 2012; Vinícius et al., 2017) package provided by the *Kepler* Guest Observer Office. After we identified the pixels that show RRL characteristics, we defined a custom aperture for each target. This step resulted in a light curve that is flawed by systematic effects or signals from other stars. Most of the systematic effects could be removed by fitting a 6th-order polynomial to the light curve in each quarter, which results in a light curve free from the systematic effects.

At the end of the quarters, the *Kepler* spacecraft turned 90 degrees so that the solar panels got enough solar illumination to function properly. This means that each star is placed on a different CCD module which introduces a systematic effect, namely a difference in the flux values compared to the previous flux values. In order to get a continuous light curve, we stitched the different quarters by applying the following method. First, we selected a reference quarter to which we aimed to stitch the rest of the quarters. Then we multiplied the pulsation amplitude in each quarter by a constant number to scale it against the reference amplitude and calculated the average fluxes for each quarter. In the final step, we subtracted the difference between the average flux of the reference and the rest of the quarters.

After the systematic effect removal and shifts, we have continuous light curves for each newly discovered RRL star. In the next section, we examine the most interesting RRL stars.

3 Results

Thanks to the PlanetHunters community and professional astronomers, our final catalog of new *Kepler* RR Lyrae stars contains 21 newly discovered RR Lyrae stars and two candidates. With these new RR Lyrae stars, we increased the number of the known RR Lyrae stars by 45% in the original *Kepler* FoV. Long cadence data are available for most of the quarters, but short cadence data are available only for one quarter for three stars.

The unmodulated RRab type stars have very stable light curves without any additional frequencies in most cases. One of them shows signs of the first overtone frequency and many combinations with the fundamental mode, and a second star has a clear sign of the second overtone frequency in its Fourier spectra. We find two RRL candidates that are close to other very bright stars. We could not detect any modulation due to high contamination from other stars. These candidates are very faint stars, and it is hard to tell the exact source of the RR Lyrae variation.

The occurrence rate of the Blazhko modulation is $\sim 46\%$ in our RRab sample excluding the two candidates. This is in good agreement with previous observations. Nearly all of the modulated stars show multiple modulation as well. The period of secondary modulation varies widely from a few tens of days to more than a thousand days. There is a possibility of a third modulation in the light curve of two different modulated stars, but the shortness of the data does not allow for a secure identification of these phenomena. The secondary modulation changes the shape of the light curve drastically, which results in a very different light curve that cannot be recognized as RR Lyrae (Fig. 2). Many additional frequencies, first and second overtone frequencies, and their combinations are visible in their Fourier spectra, e.g. period doubling is clearly visible in the light curves in Fig. 3 and Fig. 4. Nearly all Blazhko modulated stars show half-integer frequencies, but as stated in Szabó et al. (2010), the period doubling shows various strengths from Blazhko cycle to Blazhko cycle, and in some cases, it cannot be observed.

There is one modulated RRc type variable in our sample (Fig. 5), which appears

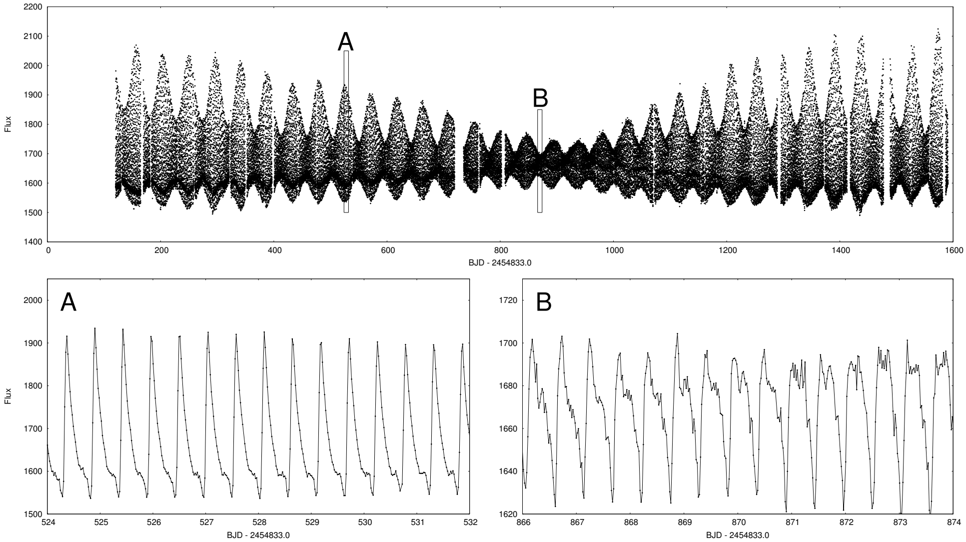

Fig. 2: Top: the light curve of a modulated RRab star. Bottom left: a zoomed view of the light curve at Blazhko maxima. Bottom right: same as left but for Blazhko minima.

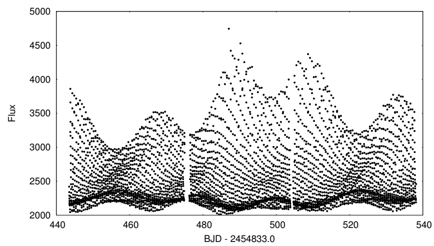

Fig. 3: Multiple Blazhko modulation is present in this star. Strong period doubling effect is also visible at Blazhko maxima.

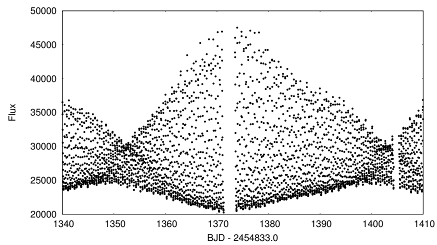

Fig. 4: A Blazhko modulated RRab star. Period doubling effect is visible at Blazhko maxima.

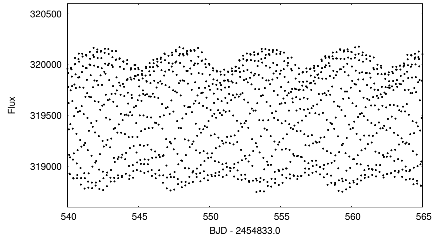

Fig. 5: Fifteen-day segment of the light curve of the modulated RRc star showing the $\sim 5.8\,\mathrm{d}$ long modulation.

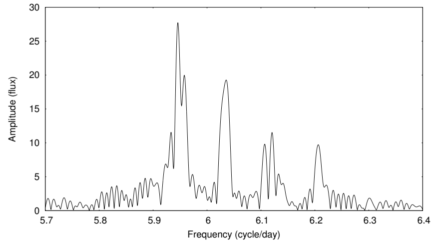

Fig. 6: Fourier spectrum of the RRc star where four peaks are visible at the frequencies corresponding to the 0.61 period ratio.

to be the first modulated RRc in the original *Kepler* FoV with a modulation period of ~ 5.8 d. Also, this RRc does not show any sign of the additional frequencies at the 0.61 period ratio. On the contrary, an unmodulated RRc (Fig. 6) shows four peaks at the 0.61 period ratio, which is the first detection in an RRc star.

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References

Benkő, J. M., et al., *MNRAS* **409**, 1585 (2010), arXiv: 1007.3928

Girardi, L., Groenewegen, M. A. T., Hatziminaoglou, E., da Costa, L., *A&A* **436**, 895 (2005), arXiv: astro-ph/0504047

Moskalik, P., et al., *MNRAS* **447**, 2348 (2015), arXiv: 1412.2272

Nemec, J. M., et al., *MNRAS* **417**, 1022 (2011), arXiv: 1106.6120

Nemec, J. M., et al., *ApJ* **773**, 181 (2013), arXiv: 1307.5820

Robin, A. C., Reylé, C., Derrière, S., Picaud, S., *A&A* **409**, 523 (2003)

Sódor, Á., Skarka, M., Liška, J., Bognár, Z., *MNRAS* **465**, L1 (2017), arXiv: 1609.06474

Still, M., Barclay, T., Astrophysics Source Code Library (2012), arXiv: 1208.004

Szabó, R., et al., *MNRAS* **409**, 1244 (2010), arXiv: 1007.3404

Vinícius, Z., et al. (2017), URL https://doi.org/10.5281/zenodo.835583