A Study of RR1 Lightcurve Modulation in OGLE-III Bulge Time-series

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Abstract

We report the results of our study of lightcurve modulation in a sample of 493 RR1 variables from the OGLE-III survey of galactic bulge fields. Each object in this list has 1500 or more I-band observations. We compare our findings with earlier studies regarding lightcurve modulation in LMC and galactic field RR1 stars. We also report the discovery of the modulated-Blazhko RR1 star OGLE-BLG-RRLYR-03825 which has a Blazhko period of 16.469 d which itself is modulated with a period of 339.2 d.

1. Introduction and Motivation

The first-overtone radial-pulsating RR Lyrae stars, known as RRc type, or RR1 in the more physically-intuitive mode-based classification system of Alcock et al. (2000), are relatively poorly studied compared to their higher-amplitude fundamental-mode counterparts, the RRab (also known as RR0) variables. In part, this situation is a legacy of the many decades of photographic variable star surveys where their smaller photometric amplitudes and more sinusoidal lightcurves resulted in fewer discoveries. These same factors also made it difficult to detect and study changes in lightcurve behavior.

It is only with the advent of wide-field, long-term photometric surveys that large numbers of galactic field RR1 stars have been identified without significant selection biases. Such surveys allow the prospect of answering questions such as:

- How does the period/amplitude modulation of RR1 stars compare to that of RR0 stars?
• Is there a period dependence of the period/amplitude modulation?

• Is there any evidence of binarity in and of the power spectra of RR1 stars and do they share the peculiar lack of detected binarity of tens of thousands of RR0 stars?

• Is there evidence of period-doubling in any RR1 time series?

• Are any more complicated or unexpected behaviors seen only in the RR0 class?

2. Photometric Time-series Source and Characteristics

The photometric precision and reliable cadence of Kepler satellite mission data would seem a natural choice for studying RR1 lightcurve behavior and the power of such data has been demonstrated by Moskalik et al. (2012). However, the Kepler field contains only four known RR1 stars and consequently ground-based surveys are still required to evaluate correlations of lightcurve behavior with other observable characteristics such as period and metallicity.

The analysis in this paper is based upon the massive photometric survey of galactic bulge fields by Soszyński et al. (2011) who reported 11,756 RR0 and 4,989 RR1 variables, respectively. Two of their key findings were that 75% of RR1 in the 0.33-0.45 d period range had detectable period changes and that “Blazhko”-like lightcurve modulation was found in 8% of the RR1 sample.

The data sample provided by Soszyński et al. (2011) is especially suitable for further time-series analysis for several reasons. First, the signal-to-noise ratio of their I-band lightcurves is typically 50:1. Second, the photometry was collected over 8 years or more, providing unusually long and uniform quality time-series. Third, galactic bulge RR1 stars are in heavily-crowded regions and the excellent seeing at the site and image scale of 0.26 arcsec/pixel are critically-important and unrivaled by other surveys. The single, unavoidable downside of studying variables in the galactic bulge is the annual interruption of observations when the Sun passes through the region.

There are a handful of more detailed studies of RR0 lightcurve modulation in the literature. Szczygieł & Fabrycky (2007) analysed galactic field RR1 stars which had V-band lightcurves available from ASAS. Of the 756 RR1 stars studied, they found 49 (i.e. 6.5%) exhibited the Blazhko effect. They also noted that 15 of the 756 RR1 stars (i.e. 2%) showed period change. Their most intriguing finding was a single RR1 star, LS Her, which appeared to show a double-Blazhko modulation. The properties of the double modulation of LS Her were more completely investigated by Wils et al. (2008) who found that it had a (quite short) Blazhko period of 12.75 days which was itself modulated with a period of 109 days. At the time, this was the only known instance of such lightcurve modulation.

Percy & Tan (2013) investigated period changes of RR1 stars which had recorded brightness maxima in the GOES database. Using 41 stars for which sufficient historical
times of maxima existed, they found lower rates of period change for RR1 stars with periods shorter than 0.25 days. They also noted that one of the well-observed galactic field RR1 stars, SX UMa, had a very unstable period.

Times of maximum are not ideal for studying the lightcurve evolution of RR1 stars because of both lightcurves features near maximum and the relatively large fraction of pulsation phase spent near maximum brightness. When sufficient photometry exists, it is always better to incorporate the whole lightcurve into the analysis.

3. Method

We chose to restrict our investigation to the RR1 time-series from Soszyński et al. (2011) which had at least 1,500 I-band measurements available. Our selection criterion resulted in 493 lightcurves.

The photometric time-series were initially analyzed using the sequential CLEANest algorithm of Foster (1995). “Sequential CLEANest” is very similar to the more common method of sequential pre-whitening in which, at each iteration, the strongest frequency in the Fourier spectrum is added to the frequency list (a set of discrete frequencies with which to model the underlying signal), and its effect removed from the data. Then a Fourier spectrum is computed from the residuals. In contrast to sequential pre-whitening, the subsequent instances of CLEANest allow all frequencies to vary whenever a new one is added to the frequency list, optimizing the frequency set at each step. Also, the discrete frequencies constituting the frequency set can be restored to the spectrum simply by plotting a line to represent them, which is most easily done by plotting an amplitude rather than power spectrum, making the line’s height equal to the amplitude of that frequency in a best-fit model to the data.

In most cases the refinement of frequencies which distinguishes sequential CLEANest from sequential pre-whitening brings about only small changes to previously determined frequencies. However, when periodic fluctuations are subject to very slow modulation, previously determined frequencies can change substantially and CLEANest will often settle on a set of very closely-spaced frequencies - often much more closely-spaced than the native resolution of the Fourier spectrum. These clusters of frequencies make for a poor - sometimes very poor - representation of the Fourier spectral density, but a superior model of the signal underlying the data.

The representation of the data from the frequencies determined by CLEANest can then be used to quantify the time-varying period, amplitude, and phase of the underlying signal, i.e. the modulation of the periodic behavior, by the method of “complex amplitude reconstruction” described by Foster (1995).

In order to plot a realistic representation of the estimated spectral density when very closely spaced frequencies are involved, the discrete frequencies from a CLEANest analysis can be combined by convolving them with a “clean beam” in exactly the same manner as the treatment of the CLEAN spectrum by Roberts et al. (1987).
For this analysis, we completed the CLEANest analysis for up to 12 statistically-significant frequencies. In most cases, fewer than six frequencies were significant.

4. A New Modulated-Blazhko RR1: OGLE-BLG-RRLYR-6387

OGLE-BLG-RRLYR-03825 is a “modulated-Blazhko” RR1 variable which shares a number of characteristics with the only other known instance of its kind, the galactic field RR1 star LS Her. LS Her’s first overtone period is 0.2308078 d; Wils et al. (2008) found it to have a Blazhko period of 12.75 d which itself was modulated with a period of 109 d. The first overtone period of OGLE-BLG-RRLYR-03825 is 0.2774114 d - based on the OGLE-III I-band photometry alone - and our analysis found the star to have a Blazhko period of 16.469 d which is modulated with a period of 339.2 d.

The section of the amplitude spectrum of OGLE-BLG-RRLYR-03825 which is wide enough to contain the fundamental frequency and its first two harmonics is shown in Figure 1. In Figure 2 a magnified section of the amplitude spectrum shows the modulation of the Blazhko period itself.

Figures 3 and 4 display the lightcurve phased with constant period and with the time-varying phase determined by our analysis removed, respectively. Removal of the time-varying phase preserves the underlying lightcurve shape for Fourier coefficient analysis. The improvement in the definition of the lightcurve shape by removing the time-varying phase is demonstrated for several other modulated lightcurves in Figures 5, 6, 7, 8, 9, 10, 11, and 12, respectively.

Wils et al. (2008) noted it is possible that other galactic field RR1 stars have modulated-Blazhko lightcurves but that the duration and quality of most existing time-series would not allow them to be easily detected. The OGLE-III bulge data is more uniform in this regard and yet this object was one of only a few modulated-Blazhko candidates, suggesting the occurrence of stars with detectable power (from ground-based surveys) in Blazhko-modulated variation is low - less than 2%.

5. Conclusions and Future Work

The principal findings of our analysis to date are:

- Lightcurve amplitude and phase modulation among RR1 stars is function of period and we find that shorter-period stars have significantly higher rates of such activity.

- A “modulated-Blazhko” star has been found - OGLE-BLG-RRLYR-03825. Like the galactic field RR1 star LS Her, it is a short-period (0.2774114 d) RR1 and the Blazhko period is short (16.469 d). The short-period Blazhko modulation itself is modulated with a 339.2 d period.
Figure 1.— The amplitude spectrum of OGLE-BLG-RRLYR-03825. Note that the fundamental (near a frequency of 3.6 d\(^{-1}\)) and its first two harmonics have adjacent Blazhko peaks which are themselves modulated.

Figure 2.— A portion of the amplitude spectrum of OGLE-BLG-RRLYR-03825 in the immediate vicinity of the fundamental mode peak near 3.6 d\(^{-1}\), revealing apparently periodic modulation of the Blazhko period itself.
Figure 3.— The I-band lightcurve of OGLE-BLG-RRLYR-03825 phased with the period 0.27741147 d.

Figure 4.— The I-band lightcurve of OGLE-BLG-RRLYR-03825 with the time-varying phase removed as determined by clusters of nearby frequencies in a CLEANest model.
Figure 5.— The I-band lightcurve of OGLE-BLG-RRLYR-06387 phased with the period 0.2717559 d.

Figure 6.— The I-band lightcurve of OGLE-BLG-RRLYR-06387 with the time-varying phase removed as determined by clusters of nearby frequencies in a CLEANest model.
Figure 7.— The I-band lightcurve of OGLE-BLG-RRLYR-08832 phased with the period 0.3036124 d.

Figure 8.— The I-band lightcurve of OGLE-BLG-RRLYR-08832 with the time-varying phase removed as determined by clusters of nearby frequencies in a CLEANest model.
Figure 9.— The I-band lightcurve of OGLE-BLG-RRLYR-09062 phased with the period 0.25949368 d.

Figure 10.— The I-band lightcurve of OGLE-BLG-RRLYR-09062 with the time-varying phase removed as determined by clusters of nearby frequencies in a CLEANest model.
Figure 11.— The I-band lightcurve of OGLE-BLG-RRLYR-13161 phased with the period $0.25375814$ d.

Figure 12.— The I-band lightcurve of OGLE-BLG-RRLYR-13161 with the time-varying phase removed as determined by clusters of nearby frequencies in a CLEANest model.
• We have seen no clear evidence of binarity to date. This is possibly due to the higher rates of non-periodic lightcurve modulation in RR1 stars swamping any existing signal due to binarity.

• Our unbiased selection of significant frequencies revealed no clear period-doubling candidates in this sample. We note that the semi-amplitudes of the period-doubling peaks detected by Moskalik et al. (2012) are similar to the detection threshold of our ground-based time-series, so this finding sets an upper limit for their typical power, if such peaks indeed exist in most RR1 stars.

We are continuing the analysis of the frequency list derived from the well-observed sample. Future opportunities for greater understanding from this rich dataset include the search for peculiar period ratios, such as those found in the only four known RR1 stars in the Kepler field by Moskalik et al. (2012), and searching for correlations between lightcurve behavior and metallicity using relations similar to those derived by Morgan et al. (2007), but adapted for I-band lightcurves.

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