The Unique Frequency Spectrum of the Blazhko RRc Star LS Her

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ABSTRACT
The Blazhko effect in RR Lyrae stars is still poorly understood theoretically. Stars with multiple Blazhko periods or in which the Blazhko effect itself varies are particularly challenging. This study investigates the Blazhko effect in the RRc star LS Her. Detailed CCD photometry in the $V$, $R_C$ and $I_C$ band has been performed on 63 nights during six months. LS Her is confirmed to have a Blazhko period of 12.75 ± 0.02 days. However, where normally the side frequencies of the Blazhko triplet are expected, an equidistant group of three frequencies is found on both sides of the main pulsation frequency. As a consequence the period and amplitude of the Blazhko effect itself vary in a cycle of 109 ± 4 days. LS Her is a unique object turning out to be very important in the verification of the theories for the Blazhko effect.

Key words: Stars: horizontal branch – Stars: oscillations – Stars: Population II – Stars: variables: RR Lyr – Stars: individual: LS Her

1 INTRODUCTION

A century after the discovery of the Blazhko effect in RR Lyrae stars (Blažek 1907), it can still not be explained theoretically in a satisfactory way (Kolenberg et al. 2006b). The Blazhko effect manifests itself in the frequency spectrum of the light variations as one or more side frequencies close to the main pulsation frequency. The beat period resulting from the interaction between the main frequency and the side frequency is called the Blazhko period. The question focuses on how many side frequencies there are. Resonance models involving non-radial pulsations with degree $\ell_1$ lead to an equidistant triplet structure that is most commonly observed: two additional frequencies, one on each side of the main frequency and at the same distance. In some cases only doublets are observed, presumably because the amplitude of the third frequency is too low to be detected. Oblique magnetic models with $\ell_2 = 1$ lead to an equidistant quintuplet structure. Recently a frequency quintuplet was found for the first time in RV UMa (Hurta et al. 2008). Although admittedly very rare, some RR Lyrae stars show two Blazhko periods. These stars pose a particular challenge for the theories.

LS Her is one of the stars known to have two Blazhko periods. It was discovered to be variable by Hoffmeister (1935) and first classified as a W UMa type eclipsing binary. Observations on six consecutive nights by Binnendijk (1971) revealed its nature as an RR Lyrae star pulsating in the first overtone mode (an RRc type object). With a period of 0.2316 days (Binnendijk 1971) it has one of the shortest periods among the RRc stars. Binnendijk also noted variations in the light curve from night to night, but did not find a beat period because of the short timespan of his observations. From the public survey data of the Northern Sky Variability Survey (NSVS; Wozniak et al. 2004, Wils et al. 2006) found LS Her to be a Blazhko star with a Blazhko period of 13 days. Szczygieł & Fabrycky (2007) found two pairs of Blazhko triplets resulting in periods of 11.5 and 12.8 days from data of the All Sky Automated Survey (ASAS-3; Pojmanski 2002).

Other Galactic examples with multiple Blazhko periods are XZ Cyg with periods of 57.5 and 41.6 days (LaCluyzé et al. 2004), UZ UMa with periods of 26.7 and 143 days (Sógor et al. 2006) and SU Col with periods of 65.8 and 89.3 days (Szczygieł & Fabrycky 2007). Unlike LS Her, all these stars are fundamental mode pulsators (RRab stars). Until recently, only a few Galactic field Blazhko RRc stars were known (Smith 1995, Kolenberg et al. 2006a). Because of its short period it is possible to observe a full pulsation cycle of LS Her during a night. Combined with its double short Blazhko cycles, this made LS Her a very interesting object for detailed study.

The spectral type of LS Her has been given as A2 (Götz & Wenzel 1960), A5 (Samus & Durlevich 2004) and F0 (McDonald 1964).

2 OBSERVATIONS
LS Her was observed on 63 nights during six months in 2007 from two private observatories. On three nights the star was observed at both observatories. More than 240 hours of CCD photometry were secured in $V$ and $I_C$, and 65 hours on 22 nights in $R_C$. The complete observation log, together with information on the instruments used, is given in Table 1.
Table 1. Observation log.

| Observer initials | Telescope       | CCD camera      | Timespan (JD-2450000) | Nbr of nights | Nbr of hours | Number of data points |
|-------------------|-----------------|-----------------|------------------------|---------------|--------------|----------------------|
| SK                | 30-cm LX200     | SBIG ST-7XMEI   | 4199-4362              | 44            | 181.1        | - 3619               |
| EB                | 20-cm C8        | SBIG ST-7XMEI   | 4206-4366              | 22            | 65.5         | 899 901 892          |
| Total             |                 |                 | 4199-4366              | 63            | 243.2        | 4512 901 4511        |

Differential photometry was performed using GSC 1507-598 or GSC 1507-660 as comparison star and GSC 1507-776 or GSC 1507-660 as check star. Nightly standard deviations on the difference between the check star and comparison star were usually around 0.01 magnitude or better. All magnitudes were reduced to a common scale assuming the difference in magnitude between GSC 1507-660 and GSC 1507-598 to be ΔV = -0.446, ΔRc = -0.254 and ΔIc = -0.060 (determined from our data on 13 nights). GSC 1507-598 was then further assumed to have V = 12.16 from ASAS-3. No instrumental corrections were applied to the data. Some nightly plots are shown in Fig. 1, together with the model fit derived in the next section.

Figure 1. V (top curve), Rc (middle) and Ic (bottom curve) data of LS Her on a number of nights. The zero points of the Rc and Ic magnitude scales have been arbitrarily chosen. Labels on the horizontal axis are HJD = 2450000. The model plots from Table 3 are shown as well.

3 FREQUENCY ANALYSIS

Period04 [Lenz & Breger 2005] was used for the frequency analysis. Table 2 gives the frequencies found in the NSVS and ASAS-3 survey data. It lists the value of the frequency, its semi-amplitude in mmag and the signal to noise ratio (S/N). Uncertainties on the given values are the standard deviations from the results obtained from Monte Carlo simulations.

The five frequencies listed in Table 2 constitute in fact two triplets around the main frequency which is common to both triplets. The two triplets were also found in our own data sets. The Blazhko (or beat) period resulting from the first triplet is 12.75 ± 0.02 days and 11.42 ± 0.04 days from the second triplet. Surprisingly however our data also revealed a third triplet, again with the side frequencies close to those of the first triplet but on the other side of those of the second triplet and at about the same distance. This third triplet corresponds to a Blazhko period of 14.45 ± 0.07 days. A schematic presentation of these frequencies is given in Fig. 2. A logarithmic scale is used for the V amplitudes.

Due to the proximity of all the side frequencies and the limitations of the procedure to find the next significant frequency in the data, it was impossible to find a good frequency fit while imposing equidistance conditions from the start (see Breger & Kolenberg 2004 for a discussion on the equidistance of the triplets). Instead, a satisfactory solution could only be found by leaving all frequencies independent of each other. In the end, when seven independent frequencies were found, it was clear that the distances to the main pulsation frequency of the frequencies on both sides of the main frequency in each triplet were equal within the uncertainties. For
example the distance to the main frequency for the most significant side peak to the right of the main frequency was found to be \( f_1 = 0.07840 \pm 0.00009 \) cycles per day (c/d), while for the peak on the left it was found to be \( f_{-1} = 0.07847 \pm 0.00006 \) c/d. Similarly the distance between the side frequencies of the first and second triplet was found to be \( f_{+2} = 0.0092 \pm 0.0007 \) c/d, and the distance for those of the first and third triplet was \( f_{-3} = 0.0093 \pm 0.0010 \) c/d. The final frequency solution was then obtained using the equidistance criterion and is listed in Table 3 Only frequencies with \( S/N > 4 \) were retained (Breger et al. 1993). In addition to amplitudes and signal to noise ratio in \( V \), \( R_C \), and \( I_r \), the phase difference of the frequencies between \( V \) and \( I_r \) are given. The latter may aid in mode identification (see e.g. Daszyńska-Daszkiewicz 2007 and references therein). The small positive phase difference for the radial mode \( f_0 \) is consistent with that found for other RR Lyrae variables (e.g. RV UMa, Hurt et al. 2008). Only one of the six side frequencies has a phase difference different from zero at the 1-\( \sigma \) level, but it is not significant at the 2-\( \sigma \) level.

Fig. 3 shows several frequency spectra created from the \( V \) data. Besides the spectral window it shows the frequency spectrum after removal of the first, second and third triplet side frequencies. It can be seen that after removing all frequencies given in Table 2 there seems to be some power left at frequencies near integer fractions of a day. The amplitude is however small, less than 6 mmag. This remaining power is possibly caused by small zero point shifts in the data from night to night, likely introduced by the corrections needed to account for the use of different comparison stars. Phase diagrams after consecutive cleaning of our \( V \) data with the three frequency triplets are given in Fig. 4.

The second and third triplets may be viewed as changing the (primary) Blazhko modulation itself. With a period of 109 ± 4 days the amount of variation in amplitude and phase will change. In the frequency spectrum this manifests itself by the side frequencies of the first Blazhko triplet being equidistant triplets themselves. In Table 3 we have therefore dubbed \( f_{c} = f_{2} - f_{1} \) as the frequency of this superposed modulation.

To illustrate the modulation of the Blazhko period, an analysis was done of small subsets of the \( V \) data set. Each subset was taken to be 25 days in length (about two Blazhko cycles), and the best fitting amplitudes and phases were determined for the pulsation frequency \( f_0 \), the main Blazhko frequencies \( f_0 + f_1 \) and \( f_0 - f_1 \), and their linear combinations. Precise determination of the frequencies themselves is rather sensitive to the distribution of the data in such a small set. Therefore the frequencies were kept fixed at the values determined from the total dataset. A change in their value would then be manifested as a change in their phase. The results of this analysis are shown in Fig. 5. The top panel shows the change in amplitude of \( f_0 \), \( f_0 + f_1 \) and \( f_0 - f_1 \), as a function of the phase in the 109-day cycle. The lower panel of Fig. 5 shows the change in phase. As there is no change in phase of the main pulsation period, it remains effectively constant during the long cycle. However, the Blazhko period appears to vary cyclically in that interval, as can be seen from the phase changes of the Blazhko frequencies.

The variation in the Blazhko modulation may perhaps be compared to the four year cycle in the Blazhko period of RR Lyrae (Dette & Szewcz 1973). However, possible splitting of the side frequencies similar to what is observed in LS Her, has not yet been detected in RR Lyrae, perhaps because of this long period and the very long data sets needed. A phase shift of the Blazhko maximum as seen at the end of a 4-year cycle in RR Lyr was not observed in LS Her.

As can be seen in Table 3 the second order triplet frequencies (around the first harmonic of the main pulsation frequency) are found for the first \((f_1)\) and second \((f_1 + f_c)\) triplet, but not for the third \((f_1 - f_c)\), presumably because their amplitude is too low. There

### Table 2. Frequencies for LS Her found in NSVS and ASAS-3 data.

| Ident. | Frequency \((c/d)\) | \(A_{NSVS}\) (mmag) | S/N | Frequency \((c/d)\) | \(A_{V}\) (mmag) | S/N |
|--------|-----------------|-----------------|----|-----------------|-----------------|----|
| \(f_0\) | 4.33262(4) | 150(4) | 39.1 | 4.33258(1) | 181(5) | 33.5 |
| \(f_0 + f_1\) | 4.41097(20) | 45(4) | 9.3 | 4.41088(8) | 58(5) | 10.8 |
| \(f_0 - f_1\) | 4.25426(20) | 27(4) | 5.6 | 4.25429(8) | 45(5) | 8.4 |
| \(f_0 + f_2\) | 4.4209(20) | 20(4) | 4.3 | 4.4209(30) | 22(7) | 4.2 |
| \(f_0 - f_2\) | 4.2451(20) | 33(4) | 6.8 | - | - | - |

**Figure 3.** Frequency spectrum of our \( V \) data for LS Her. The top panel shows the spectral window. Panels a, b and c show the spectrum after consecutively prewhitening for the first, second and third triplet respectively.
Table 3. Frequencies for LS Her detected in our data sets.

| Frequency       | (c/d)    | $A_V$ (mmag) | $S/N_V$ | $A_R$ (mmag) | $S/N_R_C$ | $A_I$ (mmag) | $S/N_I_C$ | $\Phi_V - \Phi_I$ (degrees) |
|-----------------|----------|--------------|---------|--------------|-----------|--------------|-----------|----------------------------|
| $f_0$           | 4.33261(2) | 176.3(4)     | 147.0   | 144.7(10)    | 73.2      | 108.2(4)     | 90.1      | 2.6 ± 0.3                  |
| $f_0 + f_1$     | 4.41101(15) | 55.4(7)      | 46.6    | 48.0(16)     | 24.6      | 35.3(4)      | 29.3      | −0.6 ± 1.1                 |
| $f_0 - f_1$     | 4.25421   | 44.4(5)      | 36.4    | 26.3(18)     | 13.1      | 28.3(4)      | 23.2      | 0.9 ± 1.1                  |
| $f_0 + f_1 + f_C$ | 4.42021(34) | 32.5(5)      | 27.4    | 22.5(17)     | 11.5      | 20.5(4)      | 17.0      | 0.4 ± 1.6                  |
| $f_0 - f_1 - f_C$ | 4.24501   | 26.6(5)      | 21.8    | 23.0(17)     | 11.5      | 16.6(4)      | 13.6      | 1.0 ± 2.1                  |
| $f_0 + f_1 - f_C$ | 4.40181   | 10.9(6)      | 9.1     | 7.5(4)       | 6.2       | 7.5 ± 3.8    |           |                           |
| $f_0 - f_1 + f_C$ | 4.26341   | 16.8(10)     | 13.8    | 17.2(14)     | 8.6       | 10.4(4)      | 8.6       | 7.5 ± 3.8                  |
| $2f_0$          | 8.66522   | 16.5(4)      | 18.0    | 15.9(11)     | 11.9      | 11.8(5)      | 14.1      | 4.6 ± 2.5                  |
| $2f_0 + f_1$    | 8.74362   | 13.5(4)      | 14.6    | 11.4(11)     | 8.6       | 9.6(4)       | 11.5      | −11.4 ± 3.3                |
| $2f_0 - f_1$    | 8.58681   | 10.0(4)      | 10.8    | 8.9(11)      | 6.7       | 6.8(4)       | 8.1       | 4.4 ± 3.7                  |
| $2f_0 + f_1 + f_C$ | 8.75282   | 8.4(5)       | 9.1     | 4.7(4)       | 5.6       | 5.4 ± 5.5    |           |                           |
| $2f_0 - f_1 - f_C$ | 8.57762   | 6.0(4)       | 6.5     | 3.3(4)       | 4.0       | −7.1 ± 8.4   |           |                           |
| $3f_0 + 2f_1$   | 8.82202   | 5.0(4)       | 5.4     | 3.3(4)       | 4.0       | 2.8 ± 6.4    |           |                           |
| $3f_0 - f_1$    | 12.99783  | 6.9(6)       | 7.7     | 6.0(9)       | 4.8       | 4.5(4)       | 6.3       | 2.8 ± 6.4                  |
| $4f_0$          | 12.91942  | 4.7(4)       | 5.3     | 2.9(4)       | 4.8       | 0.3 ± 9.5    |           |                           |
| $4f_0$          | 17.33043  | 4.6(5)       | 6.1     | 2.9(4)       | 4.8       | 0.3 ± 9.5    |           |                           |

Figure 4. Phase diagrams of our $V$ data for LS Her plotted with the main pulsation period of 0.230808 days. From top to bottom the data are plotted without prewhitening and then with consecutively prewhitening for the first, second and third triplet. In order not to overload the diagrams, only one out of three data points have been plotted.

Figure 5. Changes of the amplitude (top panel) and phase (bottom panel) during the long cycle of 109 days of the main pulsation frequency $f_0$ (crosses) and the Blazhko frequencies $f_0 + f_1$ (filled circles) and $f_0 - f_1$ (open circles).

is no indication of the quintuplet frequencies $f_0 \pm f_1$. However, the frequency $2f_0 + 2f_1$ has a significant amplitude in the data.
4 CONCLUSION

LS Her was found to be an RRc Blazhko star with three close Blazhko triplets around the main pulsation frequency. The side frequencies of each of the triplets are at the same distance from the main first overtone pulsation frequency. In addition, the side frequencies of the second and third triplets are at the same distance from the side frequencies of the first triplet, within uncertainties. Consequently the maximum amplitude and maximum phase shift of the Blazhko effect changes. The Blazhko effect was found to have a primary period of 12.75 days, while its influence on amplitude and phase shifts, due to the additional triplets, changes in a cycle of 109 days.

The frequency spectrum of LS Her has been found to be unique so far, but it is not excluded that other stars which are known to have two Blazhko periods also show this complex frequency structure. As their Blazhko periods are much longer, the missing triplet would also be much harder to detect. Adequate coverage of a number of consecutive Blazhko cycles would be required to reveal additional frequencies in the spectrum of a Blazhko star.

The complex frequency spectrum of LS Her cannot easily be inferred from the current theories of the Blazhko effect. LS Her is therefore an important star against which to verify any theory of the Blazhko effect.

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