

A STUDY OF DOUBLE- AND MULTI-MODE RR LYRAE VARIABLES

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Abstract. We present the results of our new study of known RR Lyrae variable stars. All observations available for these stars in the Catalina Surveys were analyzed, and double-mode variations were identified. We studied the Petersen diagram and the period distribution for the double-mode RR Lyrae variables in the Galactic field, pulsating in the first-overtone and fundamental modes. The double-peaked character of the period distribution was detected for Galactic RR(B) stars, corresponding to Oosterhoff's classes of globular clusters, which indicates that the age and evolution stage of RR(B) stars in the field and RR Lyrae variables in globular clusters are probably the same. Besides, we discovered five RRC stars with two simultaneously excited non-radial pulsations (equidistant triplets).

Key words: stars: variables: RR Lyrae

1. INTRODUCTION

For a long time, double periodicity was known for RR Lyrae members of globular star clusters. To our knowledge, the first star of this type discovered in a globular cluster was V68 in M3 (Goranskij 1981). Smith (1995) listed the double-mode RR Lyrae variables known by that time in individual clusters. Jerzykiewicz & Wenzel (1977) discovered double-mode variations of AQ Leo, the star that remained the only known double-mode RR Lyrae star in the Galactic field (with the exception of the triple-mode AC And) for more than a decade. The next two double-mode field RR Lyrae stars, EM Dra and EN Dra, were discovered by Clement et al. (1991).

For double-mode RR Lyrae stars, The General Catalogue of Variable Stars (Samus et al. 2015) uses the designation RR(B).

Systematic discoveries and investigations of field RR(B) stars were initiated by Cseresnješ (2001). In a photographic study of fields in Sagittarius, he found double-mode variations of 53 RR Lyrae stars, 40 of them believed to belong to the Sagittarius dwarf galaxy and 13, to be stars of our Galaxy. Later, the ASAS-3 (Pojmanski 2002) and NSVS (Wozniak et al. 2004) automatic sky surveys permitted the discoveries of several dozens of stars of this type. Poleski (2014) found dozens of such stars using the LINEAR data. By now, the OGLE-IV survey has

identified 174 variables of this type in the region of the Galaxy's bulge (Soszynski et al. 2014). The Catalog of periodic variable stars of the Catalina Surveys (Drake et al. 2014) considers 502 variable stars as double-mode RR Lyraes; it was later found that actually only 165 of them belonged definitely to this type (Molnar et al. 2015); even among them, a small fraction are already known double-mode stars.

Almost all currently known RR(B) variables pulsate in the fundamental mode and first overtone, with the P_1/P_0 ratios within $0.74 - 0.75$. Several stars with periods typical of RR Lyrae stars pulsate in the first and second overtones, $P_2/P_1 \approx 0.80$, but, in our opinion, it is better to count these stars among double-mode classical Cepheids: they are located near the Galactic plane and are very similar to double-mode Cepheids of the Large and Small Magellanic Clouds in the same period range. We do not know any field stars pulsating simultaneously in the first and second overtones and possessing periods typical of RR Lyrae stars at large distances from the Galactic plane.

In most cases, the dominating mode is the first overtone. Most often, the first overtone's pulsation amplitude is considerably larger than that of the fundamental mode; cases of almost the same amplitudes (but that of the first overtone being nevertheless larger) are common enough; in still rarer cases, the amplitude of the fundamental mode is slightly higher than that of the first overtone; there are only very few RR(B) stars with the fundamental mode amplitude significantly higher than that of the first overtone.

Besides RR(B) stars with two radial pulsations, there are RR Lyrae stars with one or two additional non-radial pulsations. The Blazhko effect in RRAB stars (fundamental-mode pulsators) can usually be described with a superposition of an additional non-radial mode. There exists a number of RRC stars (first-overtone pulsators) that also have one or two simultaneously detected non-radial modes. Some authors consider stars of this variability type as RRC variables with the Blazhko effect.

RRC stars with a single non-radial pulsation whose frequency is close to that of the first overtone were first discovered by Olech et al. (1999) in the globular cluster M55 (three variables). Alcock et al. (2000) identified 24 such variables in the Large Magellanic Cloud (the MACHO project; the variability type designated RR1- ν 1). A star of this kind, TYC 6556 00609 1, is known in the Galactic field (Antipin & Jurcsik 2005). The P_2/P_1 period ratios for stars of this type (assuming $P_1 > P_2$) are within $0.9 - 0.999$. The amplitude of the secondary oscillation can be considerably lower than the amplitude of the main one, but these amplitudes can also be virtually the same.

RRC stars with two simultaneously excited non-radial pulsations are often called equidistant triplets: frequency differences of the first and second non-radial modes with the main oscillation are the same, i.e. the frequency of one of the non-radial oscillations is higher than the f_1 frequency by some amount m , while the frequency of another one is lower than the f_1 frequency by the same amount m . Let us denote all the frequencies f_1 , $f_1 + m$, and $f_1 - m$. Here, the difference between adjacent frequencies is not large, like in the case of the RRC stars with a single non-radial pulsation described above.

Alcock et al. (2000) identified 28 variables of this type in the Large Magellanic Cloud (the MACHO project, the variability type designated as RR1-BL). Among stars of the Galactic field, the case of NSV 07340 = V1141 Her is known (Antipin et al. 2010, $P_1 = 0.317152$ d, $m = 0.030$ d $^{-1}$). Jurcsik et al. (2015) found several

RRC stars with non-radial pulsations in the globular cluster M3, among them the equidistant-triplet star V140 ($P_1 = 0.33316$ d, $m = 0.0689$ d⁻¹).

2. DOUBLE-MODE RR LYRAE STARS, RR(B) TYPE

Since 2007, I have performed a search for double-mode RR Lyrae variable stars using several available photometric surveys. I detected (in some cases, with co-authors) double-mode variability for 235 stars belonging to the RR(B) type, which currently represent about one third of all known RR(B) stars in the Galactic field. Most of them were discovered during the recent two years, in the course of the analysis of the Catalina Surveys data (Drake et al. 2009). Using these data, I mainly check the RRC stars with considerable scatter of data points on the light curve, among previously known as well as recently discovered stars from the Catalina Surveys periodic variable star catalog (Drake et al. 2014). The limiting magnitude in minimum brightness for the studied RR(B) stars is 19.4 mag in the Catalina Surveys photometric system (CV). The results of our search for RR(B) stars are presented in a series of papers published in *Peremennye Zvezdy/Variable Stars*. The majority of the stars (207 variables) were announced in three papers (Khruslov 2014, 2015ab). The first of these papers contains also references to earlier publications.

Among the double-mode RR Lyrae variable stars we identified, there are two interesting cases of variables with extreme periods. The star USNO-B1.0 0822-0766869 (Khruslov 2015b, No. 103) has the longest period among the RR(B) variables, $P_0 = 0.600176$ d. The light curve of USNO-B1.0 0822-0766869 is displayed in Fig. 1. A slightly longer period ($P_0 = 0.60371$ d) is known only for the star vs3f773 from Cseresnjes (2001), considered in the cited paper to belong to stars of the Sagittarius dwarf galaxy. The variable USNO-B1.0 0773-0284953 (Khruslov 2015b, No. 33) has almost the shortest fundamental-mode period among field stars at sufficiently large distances from the Galactic plane ($b = +37.4^\circ$; $P_0 = 0.447456$ d). Shorter-period RR(B) stars are known only in the direction of the Galactic center: several dozens of stars from the OGLE-III project and the star vs7f54 (Cseresnjes 2001) with $P_0 = 0.43574$ d, believed by Cseresnjes to be a variable in the Galaxy.

Besides, of interest is the rare case of USNO-B1.0 1344-0191047 (Khruslov 2014, No. 1) whose fundamental-mode amplitude is much larger than that of the first overtone. The period ratio for this star, $P_1/P_0 = 0.7460$, exceeds considerably that typical of the corresponding fundamental-mode period ($P_0 = 0.482702$ d), therefore, the star in the Petersen diagram lies much higher than other stars with similar periods.

The Petersen diagram (relating the P_1/P_0 period ratio and the logarithm of the fundamental-mode period) for all known Galactic field RR(B) F/1O variables (with the exception of the majority of stars towards the Galactic center – the Galactic bulge RR Lyrae stars from the OGLE-IV and MACHO projects and the Sagittarius dwarf galaxy stars) is displayed in Fig. 2.

Based on our results and all other information available for RR(B) stars (we did not take into account only stars towards the Galactic center from surveys like OGLE), we plotted the period distribution for the Galactic-field double-mode RR Lyrae stars. Data on 460 stars were used. The distribution, displayed in Fig. 3, is double-peaked, with the primary maximum near the period $P_0 = 0.48$ d and the secondary one near $P_0 = 0.54$ d.

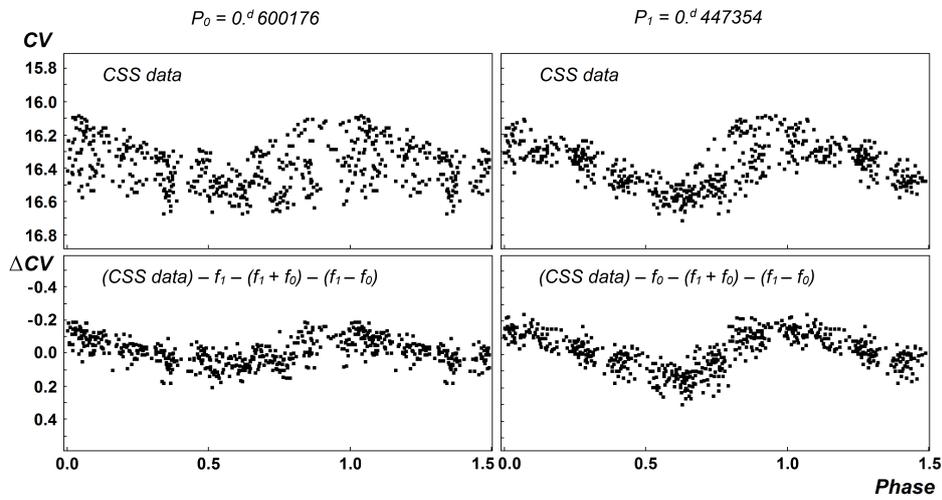


Fig. 1. The light curves of USNO-B1.0 0822-0766869 (Khruslov 2015b, No. 103). Upper panels: raw data; lower panels: the folded light curves with the other oscillation pre-whitened.

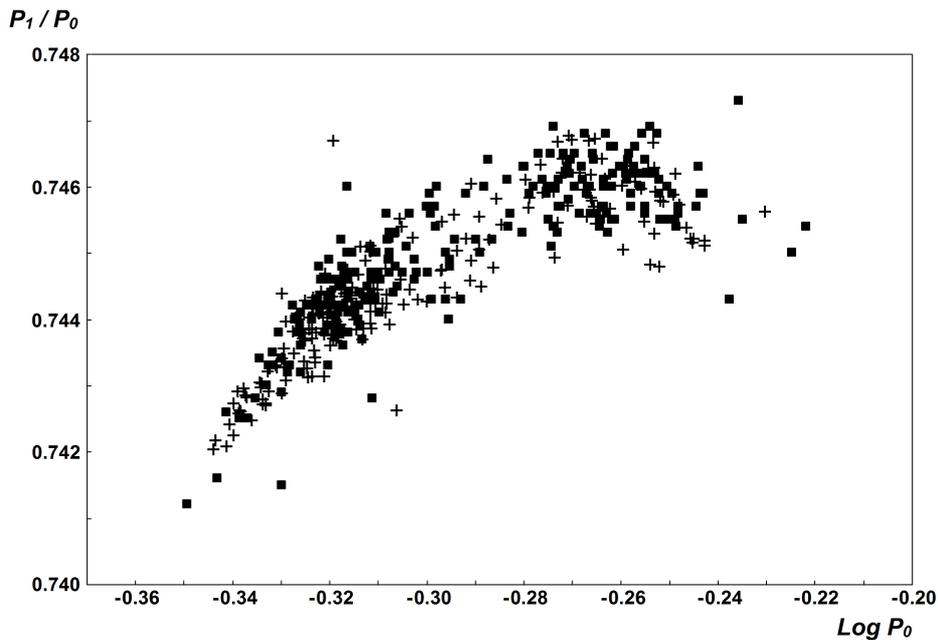


Fig. 2. The Petersen diagram for the Galactic field double-mode RR Lyrae F/10 variables. The filled squares represent the F/10 RR(B) stars identified by us and the empty triangles denote previously known RR(B) stars (according to <http://www.aavso.org/vsx/>).

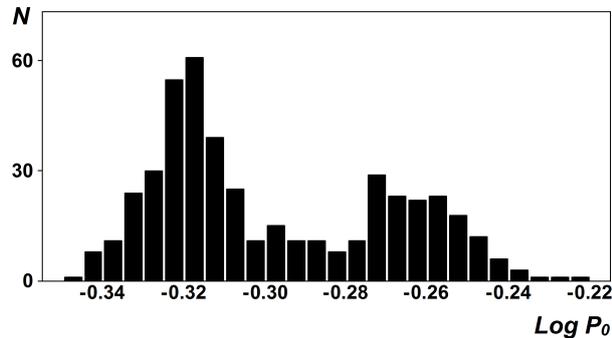


Fig. 3. The period distribution of RR(B) stars.

Earlier, the double-peaked character of the period distribution for Galactic RR(B) stars was not obvious, the amount of data for variables of this type being insufficient. A similar distribution for the Large Magellanic Cloud does not show a double-peaked character; it is marginally two-peaked for the Small Magellanic Cloud (Soszynski et al. 2010).

The two maxima of the period distribution for RR(B) stars probably coincide with the maxima of period distributions for RR(B) stars in globular clusters of Oosterhoff's classes I and II. Smith (1995), with a reference to Clement et al. (1993), presents the Petersen diagram with identified groups of RR(B) stars of the two Oosterhoff's classes. Double-mode stars in the cluster of class I (IC 4499) have periods close to that of the main maximum of the distribution for field RR(B) stars ($P_0 = 0.48$ d), while stars in class II clusters (M15 and M68) have periods close to that of the distribution's secondary maximum ($P_0 = 0.54$ – 0.55 d).

If we remember that the distribution of periods for field RR Lyrae stars does not reveal peaks or gaps corresponding to Oosterhoff's classes (Kukarkin 1975), probably due to the presence, in the Galactic field, of RR Lyrae stars with different element abundances and ages, we can assume that the detected double-peaked distribution indicates that age and evolutionary stage of RR(B) stars in the field and RR Lyrae stars in globular clusters are the same.

3. RRC STARS WITH NON-RADIAL PULSATIONS

In the search for RR Lyrae variables with two radial pulsations, F/1O, I detected 16 RRC stars with a single excited non-radial mode, its frequency close to that of the first-overtone radial mode (Khruslov 2012, 2015c).

We earlier announced discoveries of equidistant triplets for two RRC stars: TYC 3877 02198 1 (Khruslov 2010) and GSC 2010-00224 (Khruslov 2012). Later, we analyzed SuperWASP data (Butters et al. 2010) for TYC 3877 02198 1 and were not able to confirm the presence of the third frequency.

Now, we announce five more cases of RRC stars with two simultaneously excited non-radial pulsations (equidistant triplets). All these variables were previously known as RRC stars (with the exception of No. 2; Drake et al. 2014 earlier announced it as an RR(B) star). We analyzed all observations available for these stars in the Catalina Surveys online public archives using the period-search software developed by Dr. V. P. Goranskij for Windows environment.

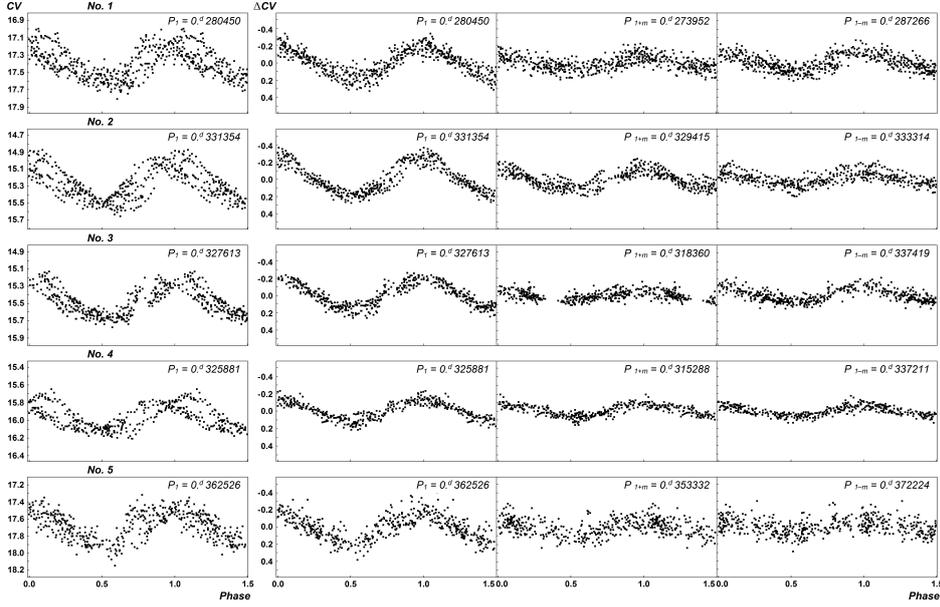


Fig. 4. The light curves of RRC stars with a single non-radial pulsation. Left-hand column of panels: raw data with the first overtone period; three right-hand columns of panels: the folded light curves with the other oscillation pre-whitened.

Table 1. Equidistant triplets: positions and magnitudes.

No.	Coordinates (2000.0)	USNO-B1.0	mag (CV)
1	03 09 49.30 +28 34 05.0	1185-0037622	17.00 – 17.75
2	11 39 37.27 –10 44 27.8	0792-0227178	14.87 – 15.66
3	13 06 10.90 –14 10 31.5	0758-0272311	15.13 – 15.78
4	16 20 25.94 +00 38 20.3	0906-0261394	15.65 – 16.21
5	16 51 26.51 +12 51 56.8	1028-0341556	17.32 – 18.15

Table 2. Equidistant triplets: light elements and amplitudes.

No.	P_1 , d	m , d^{-1}	$P_{(1+m)}$, d	$P_{(1-m)}$, d	Epoch	A
1	0.280450	0.0846	0.273952	0.287266	0.132 / 0.050 / 0.055	0.172 / 0.064 / 0.100
2	0.331354	0.01776	0.329415	0.333314	0.216 / 0.128 / 0.110	0.200 / 0.097 / 0.068
3	0.327613	0.0887	0.318360	0.337419	0.328 / 0.084 / 0.077	0.157 / 0.043 / 0.080
4	0.325881	0.1031	0.315288	0.337211	0.162 / 0.013 / 0.113	0.118 / 0.067 / 0.056
5	0.362526	0.0718	0.353332	0.372224	0.325 / 0.107 / 0.340	0.151 / 0.070 / 0.056

Information on the studied stars is presented in Tables 2 and 3. Table 1 contains the equatorial coordinates (J2000), the star number in the USNO-B1.0 catalog and the magnitudes at maximum and minimum in the Catalina photometric system. Table 2 contains the light elements and amplitudes: the first-overtone period P_1 ; frequency difference m and periods of the non-radial pulsations (frequencies $f_1 + m$ and $f_1 - m$); the first-overtone and non-radial-mode epochs

of maxima ($\text{Epoch}_1/\text{Epoch}_{1+m}/\text{Epoch}_{1-m}$; 2455000 was subtracted from all Julian dates); semi-amplitudes of the first-overtone and non-radial-mode oscillations ($A_1/A_{1+m}/A_{1-m}$).

The light curves of the five new equidistant-triplet stars are displayed in Fig. 4. Each row begins with the light curve for the period P_1 (from initial data); then follow the light curves for each of the three oscillations, the two other frequencies excluded.

The periods of dominant oscillations (first overtone, P_1) for all our equidistant triplets are within 0.280–0.363 d. As for amplitudes of the non-radial modes, the $A_{1+m} > A_{1-m}$ and $A_{1+m} < A_{1-m}$ cases are equally frequent.

4. CONCLUSIONS

Our new study of known RR Lyrae variable stars from the Catalina Surveys data that has revealed a number of new double-mode variables increases considerably the material available for future statistical analysis. The two-peaked character of the period distribution was detected for Galactic RR(B) stars, corresponding to Oosterhoff's classes of globular clusters. The five new cases of equidistant triplets are among the first ones identified in the Galaxy's field. We found that the phased light curves of double-mode stars, plotted with the first-overtone period, have a typical shape and scatter, therefore it is possible to preliminary identify (prior to the frequency analysis) equidistant-triplet stars among other RRC variables.

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