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## New Double-Mode RR Lyrae Variables

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We present a new study of 28 known RR Lyrae variable stars. We analyzed all observations available for these stars in the Catalina Surveys, LINEAR, Northern Sky Variability Survey, and SuperWASP online public archives using the period-search software developed by Dr. V.P. Goranskij for Windows environment. According to these data, the stars are double-mode RR Lyrae variables, pulsating in the first-overtone and fundamental modes.

## 1 Introduction

According to the International Variable Star Index (VSX, AAVSO), about 600 double-mode RR Lyrae variable stars are currently known in our Galaxy, usually pulsating in the fundamental and first overtone radial modes (most of them, outside globular clusters). During the recent years, automated data surveys resulted in a considerable progress in the identification of stars of this type. Wils (2010) reported seven new RR(B) stars from WASP data. About 90 RR(B) stars in the bulge of our Galaxy were found in the OGLE project (Soszynski et al. 2011). In the Catalina Surveys Periodic Variable Star Catalog (Drake et al. 2014), results are presented for 502 RR(B) stars, at least 300 of them previously unknown. Then, a discovery of 59 new Galactic double-mode RR Lyrae stars found in the LINEAR survey data (a small part of them were found earlier by other authors) was reported by Poleski (2014). The author of the present paper, with his co-authors, earlier discovered 28 double-mode RR Lyrae variable stars, pulsating in the fundamental and first overtone radial modes (Khruslov 2007, 2010, 2011, 2012a, 2012b; Khruslov, Huemmerich, and Bernhard 2013; Antipin and Khruslov 2013; Huemmerich and Khruslov 2014).

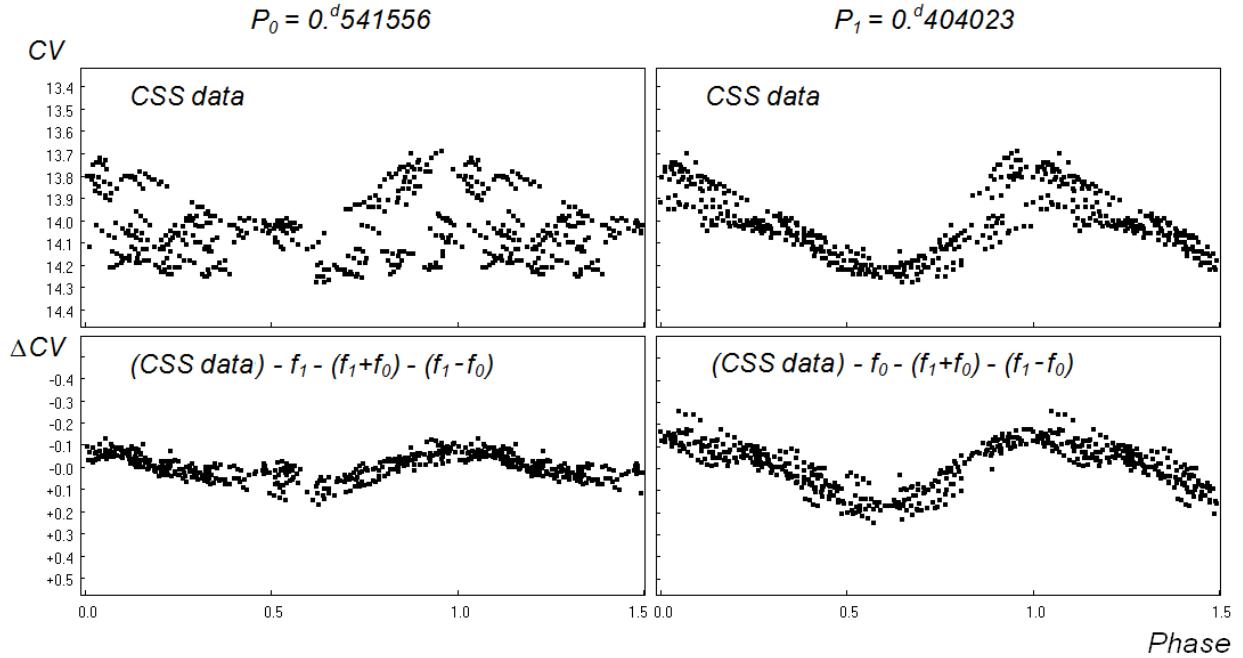
In this article, I present the discovery of 28 more double-mode RR Lyrae variable stars, pulsating in the first-overtone and fundamental modes.

## 2 Results

I studied 28 known RR Lyrae variable stars, analyzing all observations available for them in the Catalina Surveys (Drake et al. 2009), LINEAR (Sesar et al. 2011), Northern Sky Variability Survey (NSVS , Wozniak et al. 2004), and SuperWASP (Butters et al. 2010) online public archives using the period-search software developed by Dr. V.P. Goranskij for Windows environment. According to these data, the variables are double-mode RR Lyrae variables, pulsating in the first-overtone and fundamental modes.

Light curves, finding charts, and data (CSS, SSS, MLS, LINEAR, NSVS, SWASP) are available online in the html version of this paper as a zip-archive. The light curves

are given in the format displayed in Fig. 1. Top panels present data folded with the fundamental-mode and first overtone periods. Bottom panels show the same curves after prewhitening the other oscillation (if the frequencies  $f_1 + f_0$  and  $f_1 - f_0$  were excluded, it is also noted). These light curves are given for all data series. In three cases (No. 16, 19, 20), the data from LINEAR and Catalina surveys could not be represented with a unified system of light elements, probably indicating that both periods,  $P_1$  and  $P_0$ , vary.

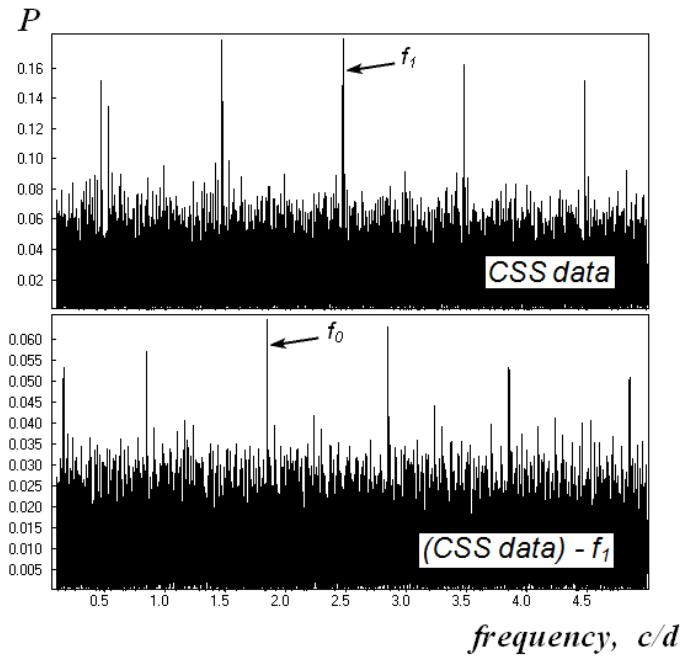


**Figure 1.**

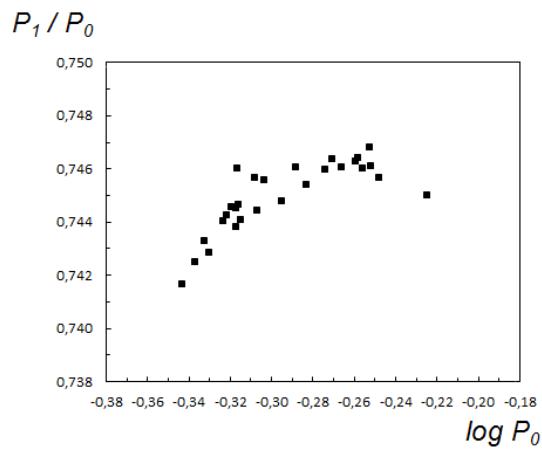
The light curve of GSC 0923-00144 (No. 18).

Along with the light curves, we present power spectra of the RR Lyrae variables, for the raw data and after subtraction of the first-overtone (or fundamental mode) oscillations, as is shown in Fig. 2. The structure of the power spectra shows that the secondary periods are real.

Their period ratios,  $P_1/P_0$ , are typical of radially pulsating double-mode RR Lyrae stars. The Petersen diagram for double-mode RR Lyrae variables of this article is displayed in Fig. 3.

**Figure 2.**

The power spectra of GSC 0923-00144 (No. 18) for the frequencies  $f_1$  and  $f_0$ .

**Figure 3.**

The Petersen diagram for the program double-mode RR Lyrae stars.

Information on the studied stars is presented in Tables 1–4. Table 1 contains numbers from the GSC and USNO-B1.0 catalogs; equatorial coordinates (J2000); type and period previously known for the star, according to references from the last column, explained below the table. The tabulated coordinates of the variables were drawn from either the GSC2.3 (Lasker et al. 2008; star No. 1 in this paper) or 2MASS catalogs (Skrutskie et al. 2006).

**Table 1.**

No.	Name	Coordinates (J2000)	Type	P, days	Ref
1	USNO-B1.0 1344-0191047	07 <sup>h</sup> 44 <sup>m</sup> 54 <sup>s</sup> .85 +44°29'09".6	RRAB	0 <sup>d</sup> 4827138	1
2	USNO-B1.0 1315-0208615	09 38 03.96 +41 33 45.2	RRC	0.358592	2
3	USNO-B1.0 1338-0210776	09 59 38.04 +43 52 45.6	RRAB	0.4845666	1
4	USNO-B1.0 1336-0219968	10 54 18.77 +43 40 37.8	RRC	0.370803	2
5	USNO-B1.0 0738-0239220	11 14 36.57 -16 10 46.1	RRC	0.388355	2
6	GSC 5512-01099	11 25 21.23 -11 16 10.3	RRC	0.35973	3
7	USNO-B1.0 1349-0226600	11 33 51.94 +44 57 39.9	RRC	0.353188	2
8	USNO-B1.0 1102-0220937	12 47 46.30 +20 15 48.0	RRC	0.384393	2
9	USNO-B1.0 1329-0290328	12 50 17.77 +42 57 29.8	RRC	0.356830	2
10	USNO-B1.0 0863-0260489	13 16 41.33 -03 36 14.6	RRC	0.417676	2
11	GSC 0897-00784	13 19 46.77 +14 40 21.8	RRAB	0.460444	2
12	USNO-B1.0 1161-0225607	13 56 45.27 +26 06 41.0	RRC	0.397025	2
13	USNO-B1.0 1017-0252244	14 24 54.23 +11 47 45.2	RRAB	0.465064	2
14	USNO-B1.0 1121-0267760	14 25 47.22 +22 10 08.6	RRC	0.400458	2
15	USNO-B1.0 1226-0288064	14 36 49.56 +32 39 50.8	RRAB	0.4935225	1
16	USNO-B1.0 1100-0231107	14 40 18.08 +20 01 32.0	RRC	0.421228	2
17	USNO-B1.0 1295-0254008	14 53 55.16 +39 32 21.1	RRC	0.354983	2
18	GSC 0923-00144	15 13 07.59 +12 08 03.6	RRC	0.404021	2
19	USNO-B1.0 1265-0234869	15 46 19.18 +36 34 05.2	RRC	0.413950	2
20	USNO-B1.0 1039-0242114	15 49 41.38 +13 59 35.6	RRC	0.444205	2
21	USNO-B1.0 1088-0244594	15 54 04.37 +18 51 20.6	RRC	0.358311	2
22	USNO-B1.0 1182-0267691	16 01 28.46 +28 15 53.4	RRC	0.411701	2
23	USNO-B1.0 1023-0310699	16 08 25.22 +12 19 08.4	RRC	0.366803	2
24	USNO-B1.0 1084-0260951	16 24 27.51 +18 24 49.9	RRC	0.417560	2
25	USNO-B1.0 1381-0302066	16 39 13.41 +48 11 02.8	RRC	0.377389	2
26	USNO-B1.0 0667-0901820	19 52 26.89 -23 17 54.3	RRC:	0.33662	4
27	USNO-B1.0 0820-0768849	21 17 23.39 -07 59 10.9	RRAB	0.4679295	1
28	USNO-B1.0 0680-1002029	21 17 28.18 -21 56 09.0	RR:	—	5

References in Table 1:

1. Drake et al. (2013)
2. Palaversa et al. (2013)
3. Hadon, VS-COMPAS team, 2012  
( <http://www.vs-compas.belastro.net/stars/by/type/RRC> )
4. Otero, International Variable Star Index, 2014
5. Keller et al. (2008)

Table 2 presents identification numbers for the LINEAR database, other data used in the analysis, magnitude in the maximum and minimum in the Catalina surveys and LINEAR photometric systems.

**Table 2. Data.**

No.	LINEAR ID	Other data	CSS magnitude	LINEAR magnitude
1	–	CSS	17 <sup>m</sup> 8–18 <sup>m</sup> 8	–
2	16982312	CSS	16.30–17.07	16 <sup>m</sup> 40–17 <sup>m</sup> 20
3	17701631	CSS	16.29–17.11	16.38–17.18
4	23389584	CSS	15.26–15.77	15.35–15.87
5	851716	CSS, SSS	15.86–16.65	15.93–16.60
6	–	CSS, SSS, NSVS	13.32–13.98	–
7	1643135	CSS	16.13–16.84	16.22–17.17
8	4435791	CSS	16.29–16.86	16.37–16.94
9	7892817	CSS	15.75–16.39	15.82–16.49
10	8854060	CSS, MLS	16.59–17.26	16.6–17.3
11	8658610	CSS	13.62–14.41	13.75–14.54
12	10278022	CSS	16.18–16.76	16.18–16.84
13	11697185	CSS	15.56–16.38	15.71–16.46
14	11763086	CSS	15.74–16.35	15.89–16.46
15	12199470	CSS	15.18–15.95	15.33–16.03
16	12432893	CSS	16.13–16.74	16.29–16.90
17	12896695	CSS	15.47–16.05	15.63–16.39
18	13754273	CSS	13.69–14.28	13.87–14.46
19	15450888	CSS	15.63–16.25	15.81–16.35
20	15269598	CSS	15.96–16.61	16.07–16.72
21	15708768	CSS	15.75–16.29	15.67–16.39
22	16182003	CSS	15.04–15.62	15.18–15.73
23	16456815	CSS	15.25–15.86	15.45–15.98
24	18255554	CSS	14.67–15.23	14.80–15.27
25	18861334	CSS	15.83–16.53	15.93–16.68
26	–	SSS, 1SWASP	14.82–15.35	–
27	–	CSS	14.94–15.74	–
28	–	CSS	15.35–15.92	–

Light elements of all oscillations: the first-overtone period  $P_1$ , the fundamental period  $P_0$ , the first-overtone and fundamental mode epoch of maxima, period ratios  $P_1/P_0$ , periods of the frequencies  $f_1 + f_0$  ( $P_{1+0}$ ) and  $f_1 - f_0$  ( $P_{1-0}$ ) are collected in Table 3.

**Table 3. Light elements.**

No.	$P_1$ , d	$P_0$ , d	Epoch <sub>1</sub> , JD	Epoch <sub>0</sub> , JD	$P_1/P_0$	$P_{1+0}$ , d	$P_{1-0}$ , d
1	0.360108	0.482702	2455000.713	2455000.795	0.7460	–	–
2	0.358595	0.481662	2454500.245	2454500.100	0.7445	0.205560	–
3	0.360565	0.484580	2455000.700	2455000.535	0.7441	0.206736	1.4089
4	0.370794	0.497336	2455000.260	2455000.137	0.7456	–	–
5	0.388360	0.521023	2454500.080	2454500.500	0.7454	0.222508	–
6	0.359729	0.483101	2455000.766	2455000.790	0.7446	–	–
7	0.353195	0.474709	2454500.329	2454500.156	0.7440	0.202515	1.3798
8	0.384402	0.515253	2454500.205	2454500.293	0.7460	0.220153	1.51369
9	0.356830	0.479250	2454500.360	2454500.395	0.7446	–	–
10	0.417684	0.559293	2455000.120	2455000.525	0.7468	–	–
11	0.341883	0.460448	2454500.333	2454500.397	0.7425	0.1962004	1.3277
12	0.397031	0.532235	2454500.146	2454500.410	0.7460	–	–
13	0.345662	0.465042	2454500.220	2454500.354	0.7433	0.198282	1.34650
14	0.400452	0.536540	2454500.400	2454500.100	0.7464	–	–
15	0.367380	0.493517	2455000.602	2455000.795	0.7444	0.210603	–
16	0.421213	0.564890	2455000.410	2455000.120	0.7457	0.241131	–
17	0.354990	0.476987	2454500.125	2454500.326	0.7442	–	–
18	0.404023	0.541556	2454500.400	2454500.150	0.7460	0.231394	1.59105
19	0.413934	0.554870	2455000.075	2455000.135	0.7460	0.237077	1.62964
20	0.444237	0.596277	2455000.088	2455000.086	0.7450	–	–
21	0.358319	0.481733	2454500.260	2454500.385	0.7438	0.205477	–
22	0.411690	0.551550	2454500.272	2454500.353	0.7464	–	–
23	0.366799	0.491922	2454500.223	2454500.168	0.7456	0.210121	1.44205
24	0.417557	0.559638	2454500.065	2454500.450	0.7461	0.239133	1.64475
25	0.377393	0.506715	2454500.070	2454500.505	0.7448	–	–
26	0.33662	0.45389	2454150.080	2454150.203	0.7416	0.193312	–
27	0.347610	0.467934	2455000.820	2455000.851	0.7429	0.1994484	1.35183
28	0.410838	0.550510	2455000.847	2455000.720	0.7463	–	–

Table 4 presents semi-amplitudes of all the oscillations, separately for Catalina surveys and LINEAR data: semi-amplitudes of first-overtone ( $A_1$ ) and fundamental mode ( $A_0$ ) oscillations, for the  $f_1 + f_0$  ( $A_{1+0}$ ) and  $f_1 - f_0$  ( $A_{1-0}$ ) frequencies. Asterisks mark the amplitudes based on other data, as explained in Comments, also containing additional information about some of the stars.

**Table 4. Semi-amplitudes.**

No.	CSS magnitude				LINEAR magnitude			
	$A_1$	$A_0$	$A_{1+0}$	$A_{1-0}$	$A_1$	$A_0$	$A_{1+0}$	$A_{1-0}$
1	0.096	0.240	—	—	—	—	—	—
2	0.173	0.114	0.053	—	0.145	0.112	—	—
3	0.148	0.135	0.052	0.037	0.219	0.164	—	—
4	0.182	0.034	—	—	—	—	—	—
5	0.163	0.132	0.046	—	0.208	0.064	—	—
6	0.183	0.082	—	—	0.127*	0.049*	—	—
7	0.156	0.104	0.032	0.041	0.113	0.065	—	—
8	0.143	0.058	0.030	0.021	0.153	0.072	0.035	—
9	0.189	0.100	—	—	0.166	0.085	—	—
10	0.162	0.050	—	—	—	—	—	—
11	0.183	0.170	0.075	0.029	0.145	0.158	0.058	0.021
12	0.159	0.045	—	—	0.150	0.057	—	—
13	0.149	0.166	0.063	0.037	0.165	0.116	0.081	—
14	0.166	0.070	—	—	0.141	0.065	—	—
15	0.141	0.122	0.049	—	0.163	0.114	0.046	—
16	0.137	0.063	0.025	—	0.148	0.055	—	—
17	0.150	0.080	—	—	0.159	0.109	—	—
18	0.146	0.065	0.032	0.026	0.167	0.076	—	—
19	0.173	0.069	0.036	0.022	0.132	0.057	0.037	—
20	0.146	0.103	—	—	0.164	0.066	—	—
21	0.164	0.052	0.023	—	0.172	0.063	—	—
22	0.177	0.065	—	—	0.141	0.058	—	—
23	0.177	0.059	0.022	0.025	0.166	0.048	—	—
24	0.139	0.055	0.023	0.017	0.154	0.038	—	—
25	0.167	0.132	—	—	0.150	0.099	—	—
26	—	—	—	—	0.035*	0.015*	0.007*	—
27	0.156	0.155	0.057	0.036	—	—	—	—
28	0.172	0.115:	—	—	—	—	—	—

**Comments:**

No. 1. A rare case when the amplitude of the first overtone mode is much lower than that of the fundamental mode.

No. 6. The variability of GSC 5512-01099 was discovered by Siarhey Hadon, project VS-COMPAS (2012), from ROTSE-I/NSVS data (NSVS 15876164). Combined brightness of several stars was measured in the NSVS, the corresponding amplitudes are somewhat too low. The ROTSE data with photometric correction flags (usually rejected) were kept for the analysis. Asterisks in Table 4 mark the semi-amplitudes in the NSVS photometric system.

No. 16. Two systems of light elements were derived. The light elements for the CSS data are given in Table 3. The light elements for the Linear data are:

$$\text{JD(max)} = 2453600.273 + 0.421227 \times E \text{ (the first-overtone period);}$$

$$\text{JD(max)} = 2453600.363 + 0.564883 \times E \text{ (the fundamental mode period).}$$

No. 19. Two systems of light elements. The light elements for the CSS data are given in Table 3. The light elements for the Linear data are:

$$\text{JD(max)} = 2453600.125 + 0.413947 \times E \text{ (the first-overtone period);}$$

$$\text{JD(max)} = 2453600.225 + 0.554846 \times E \text{ (the fundamental mode period).}$$

No. 20. Two systems of light elements. The light elements for the CSS data are given in Table 3. The light elements for the Linear data are:

$$\text{JD(max)} = 2453600.300 + 0.444207 \times E \text{ (the first-overtone period);}$$

$$\text{JD(max)} = 2453600.065 + 0.596291 \times E \text{ (the fundamental mode period).}$$

No. 26. The variability of USNO-B1.0 0667-0901820 was discovered by Luyten (1938), who did not provide accurate coordinates. In the NSV catalog (Samus et al. 2007–2012), the star is numbered NSV 12483, the catalog position of NSV 12483 marked with a crosshair in our finding chart. Its type or period are not contained in the NSV catalog. The variability of USNO-B1.0 0667-0901820 was also reported by Keller et al. (2008; Id. 109453.71). The International Variable Star Index (VSX, AAVSO), based on Catalina survey data, gives the type RRC: (a possible RRC star) for the variable; initially, two periods were given, 0.201067 days and 0.290046 days. Later, in 2014, S. Otero gave it the period  $P = 0.33662$  days, with the following remark: “It might be a double-mode pulsator (RRD) with a possible secondary period of 0.45397 d. (period ratio 0.7415) but more data are needed”. I confirm the double-mode nature of this RR Lyrae variable, based on SWASP data. Combined brightness of two stars, USNO-B1.0 0667-0901820=var and the brighter neighbor GSC 6891-00928, was measured in the SWASP data, so the corresponding amplitudes are considerably underestimated. When plotting the phased light curves for the identified frequencies,  $f_1$  and  $f_0$ , I also subtracted variations of the mean brightness in the 1SWASP data, probably of instrumental origin. I considered the JD2453860–2454388 time range in the 1SWASP data. According to SSS data, it is USNO-B1.0 0667-0901820 that varies, and GSC 6891-00928 is a constant star. I was not able to reliably detect the double-mode behavior in the SSS data. Table 4 gives the combined-brightness semi-amplitudes in the SWASP photometric system. The Super-WASP observations are available as FITS tables, which were converted into ASCII tables using the OMC2ASCII program as described by Sokolovsky (2007).

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