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New Double-Mode RR Lyrae Variables II

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We present a new study of 56 known RR Lyrae variable stars from the Catalina surveys periodic variable star catalog. We analyzed all observations available for these stars in the Catalina Surveys 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. The author of the present paper, with his co-authors, earlier discovered 56 double-mode RR Lyrae variable stars, pulsating in the fundamental and first-overtone radial modes (Khruslov 2007, 2010, 2011, 2012ab; Khruslov, Huemmerich, and Bernhard 2013; Antipin and Khruslov 2013; Huemmerich and Khruslov 2014; Khruslov 2014). In this article, I present the discovery of additional 56 double-mode RR Lyrae variable stars, pulsating in the first-overtone and fundamental modes.

2 Results

I studied 56 known RR Lyrae variable stars from the Catalina surveys periodic variable star catalog (Drake et al. 2014), analyzing all observations available for them in the Catalina Surveys (Drake et al. 2009) and SuperWASP (Butters et al. 2010) online public archives using the period-search software developed by Dr. V.P. Goranskij for Windows environment. The SuperWASP observations are available as FITS tables, which were converted into ASCII tables using the OMC2ASCII program as described by Sokolovsky (2007). In the Catalina surveys periodic variable star catalog, all these variables are designated as RRC stars. Our analysis of the available data demonstrates that 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, 1SWASP) 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.

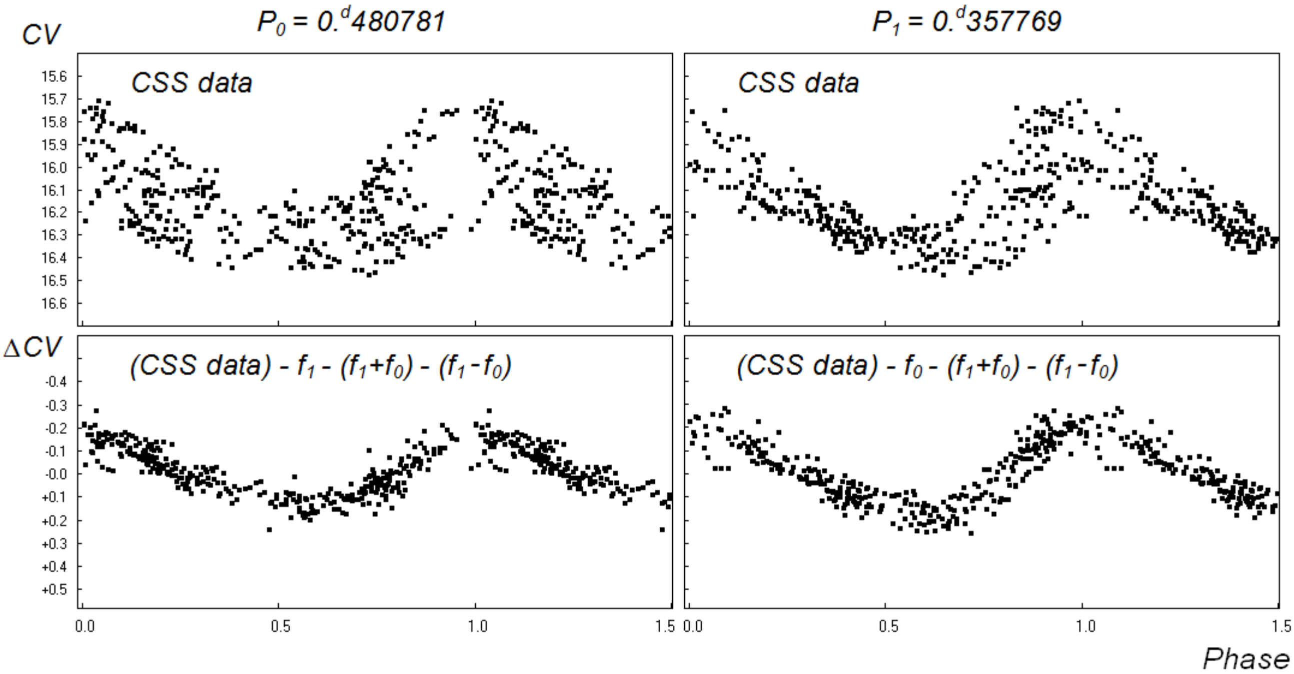

Figure 1.
The light curve of USNO-B1.0 1155-0026482 (No. 3).

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 shown in Fig. 2. The structure of the power spectra shows that the secondary periods are real.

The stars' 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 from this paper is displayed in Fig. 3.

In five cases, the periods presented in the Catalina surveys periodic variable star catalog are wrong. For Nos. 18, 28, and 56, the catalog period is a one-day alias of the real first overtone period; for Nos. 12 and 29, the catalog period is a one-day alias of the real fundamental mode period.

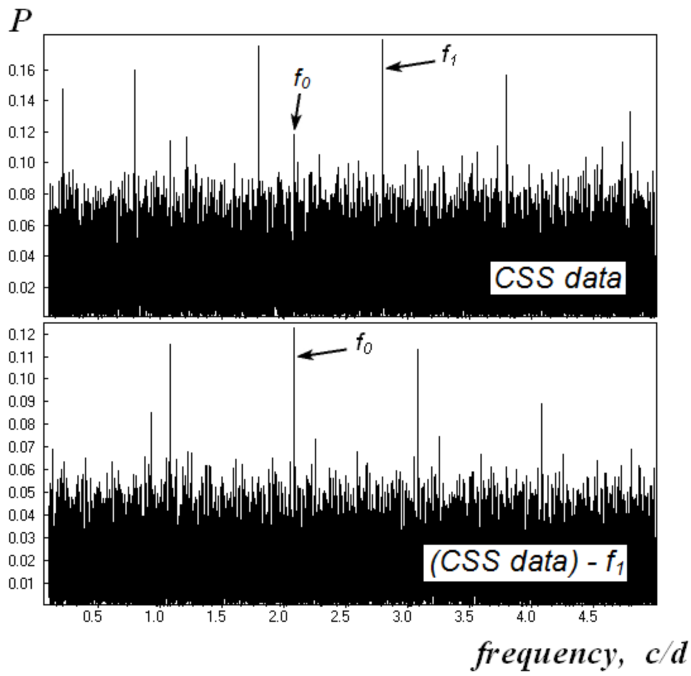

Figure 2.
The power spectra of USNO-B1.0 1155-0026482 (No. 3) for the frequencies f_1 and f_0.

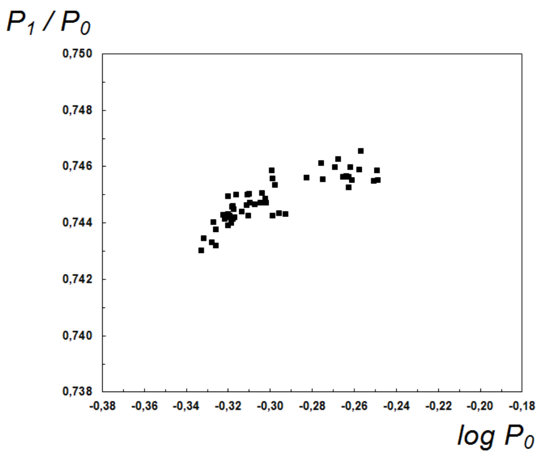

Figure 3.
The Petersen diagram for the program double-mode RR Lyrae stars.

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); magnitude at maximum and minimum in the Catalina surveys photometric system; period previously known for the star, according to the Catalina surveys periodic variable star catalog. Asterisks mark the presence of additional information on the star, as explained in Comments. The tabulated coordinates of the variables were drawn from either the GSC2.3 (Lasker et al. 2008) or 2MASS (Skrutskie et al. 2006) catalogs.

Table 1. Positions, magnitudes, and periods

No.	Name	Coordinates (J2000)	CSS mag	P, days
1	USNO-B1.0 1201-0009113	$00^h39^m38\overset{s}{.}38$ $+30°09'40\overset{''}{.}8$	16.91–17.67	$0\overset{d}{.}3951946$
2	GSC 1206-01674	01 53 42.59 +15 52 15.6	14.64–15.19	0.4205069
3	USNO-B1.0 1155-0026482	02 15 54.78 +25 34 39.6	15.71–16.48	0.357762
4	USNO-B1.0 1012-0025337	02 48 18.04 +11 12 40.5	15.94–16.65	0.418635
5	USNO-B1.0 1538-0156471	07 01 44.47 +63 53 02.7	15.98–16.57	0.3566511
6	USNO-B1.0 1021-0178560	08 09 35.30 +12 09 00.3	16.55–17.33	0.3713580
7	USBO-B1.0 1211-0158004*	08 14 29.85 +31 11 15.3	16.86–17.60	0.3508887
8	USNO-B1.0 0994-0170746	08 16 52.42 +09 27 56.7	16.47–17.29	0.3582525
9	USNO-B1.0 1087-0165074	08 24 26.28 +18 42 28.7	16.51–17.38	0.3765145
10	USNO-B1.0 1142-0160444	08 45 29.36 +24 16 31.2	17.55–18.47	0.3597362
11	USN0-B1.0 0998-0182783	08 48 38.26 +09 51 14.9	16.73–17.48	0.3560988
12	USNO-B1.0 0995-0182765	08 52 13.29 +09 32 16.1	18.1 –19.0	0.3281944
13	USNO-B1.0 1265-0169434*	08 58 09.48 +36 31 21.4	16.61–17.44	0.3558720
14	USNO-B1.0 0971-0212517	09 16 37.72 +07 11 25.3	16.55–17.30	0.404839
15	USNO-B1.0 1061-0174839	09 43 11.02 +16 09 53.5	16.70–17.49	0.3791779
16	USNO-B1.0 1083-0199119	09 55 44.88 +18 23 07.8	16.54–17.37	0.3753066
17	USNO-B1.0 1220-0203005	09 57 25.89 +32 01 17.6	17.51–18.31	0.3889338
18	USNO-B1.0 1119-0202036	10 06 44.06 +21 56 59.4	17.5 –18.4	0.283598
19	USNO-B1.0 0903-0190606	10 23 08.54 +00 23 30.4	18.4 –19.3	0.354036
20	USNO-B1.0 1059-0190499	10 23 47.66 +15 59 12.3	17.3 –18.1	0.3745709
21	USNO-B1.0 1326-0262115	10 24 57.50 +42 40 22.2	17.02–17.73	0.4086693
22	USNO-B1.0 0972-0231646	10 34 06.66 +07 12 07.9	17.40–18.25	0.3504379
23	USNO-B1.0 0875-0290446	10 42 07.92 –02 29 56.8	17.11–17.91	0.4200851
24	USNO-B1.0 0866-0219758	10 44 18.73 –03 18 50.9	16.79–17.68	0.3636318
25	USNO-B1.0 1076-0231367	11 03 51.80 +17 36 09.9	17.58–18.49	0.358411
26	USNO-B1.0 1139-0181861	11 16 44.95 +23 59 28.2	17.50–18.44	0.4130053
27	USNO-B1.0 1072-0234586	11 19 22.51 +17 13 23.7	16.87–17.60	0.3646734
28	USNO-B1.0 0877-0319036	11 28 45.50 –02 16 00.7	17.2 –18.1	0.2570875
29	USNO-B1.0 1129-0228008	11 33 27.98 +22 59 21.5	16.81–17.62	0.324888
30	USNO-B1.0 1075-0239855	11 45 17.70 +17 31 16.1	16.91–17.64	0.40805
31	USNO-B1.0 1038-0192883	11 46 31.44 +13 51 59.4	17.39–18.33	0.3511538
32	USNO-B1.0 0783-0261258	12 12 50.62 –11 39 08.5	16.80–17.55	0.3614389
33	GSC 5533-00078	12 27 26.34 –13 00 28.3	15.19–15.75	0.3642299
34	USNO-B1.0 1005-0208522	12 38 15.56 +10 35 31.3	17.34–18.31	0.3700176
35	USNO-B1.0 0997-0233324*	12 53 47.39 +09 43 09.1	15.66–16.24	0.3690403
36	USNO-B1.0 1041-0224476	13 08 47.87 +14 10 12.2	16.75–17.51	0.34526
37	USNO-B1.0 0990-0227417	13 21 53.28 +09 01 31.4	17.8 –18.7	0.3547121
38	USNO-B1.0 1162-0217838	13 23 22.11 +26 13 43.7	17.46–18.33	0.3544163
39	USNO-B1.0 1244-0215132	14 21 58.72 +34 27 24.4	16.16–16.78	0.3564981
40	USNO-B1.0 1240-0222201	14 44 01.00 +34 02 43.6	16.59–17.42	0.4070824
41	USNO-B1.0 1247-0222564	15 03 58.26 +34 46 47.4	17.02–17.87	0.357288
42	USNO-B1.0 0965-0243978*	15 08 17.61 +06 32 13.2	16.82–17.46	0.4119803
43	USNO-B1.0 1308-0273169	16 46 47.65 +40 51 16.5	16.40–17.08	0.3739999
44	USNO-B1.0 1147-0245047	16 48 59.11 +24 43 55.6	16.53–17.21	0.4011456

Table 1 Positions, magnitudes, and periods (continued)

No.	Name	Coordinates (J2000)	CSS magn.	P, days
45	USNO-B1.0 1116-0277997	16 57 09.73 +21 40 02.0	16.57–17.50	0.3648103
46	USNO-B1.0 1108-0268087	16 57 40.31 +20 53 33.7	16.08–16.65	0.3744385
47	USNO-B1.0 1057-0629220	21 48 53.46 +15 45 20.6	17.66–18.49	0.3558251
48	USNO-B1.0 1035-0607825	21 56 54.02 +13 31 24.7	16.13–16.70	0.406222
49	USNO-B1.0 1063-0609449	22 17 47.44 +16 19 29.8	17.21–17.98	0.4070613
50	GSC2.3 N09A000095*	22 27 17.66 +25 20 08.4	14.66–15.13	0.402694
51	USNO-B1.0 1016-0656702*	22 34 30.58 +11 39 12.6	16.81–17.43	0.3888151
52	USNO-B1.0 1233-0612339*	22 40 00.25 +33 22 37.6	14.51–15.11	0.357745
53	USNO-B1.0 1092-0590255	22 43 20.23 +19 14 33.1	16.58–17.32	0.35608
54	USNO-B1.0 1161-0575560	22 51 17.35 +26 10 54.5	17.10–17.75	0.3715164
55	USNO-B1.0 0989-0604703	22 55 42.42 +08 59 36.2	15.41–16.07	0.3492836
56	GSC 2255-01669*	23 49 00.58 +27 03 16.4	13.62–14.29	0.2682041

Light elements of all oscillations: the first-overtone period P_1, fundamental period P_0, first-overtone and fundamental mode epoch of maxima, period ratio 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 2.

Table 2. Light elements

No.	P_1, d	P_0, d	Epoch$_1$, JD	Epoch$_0$, JD	P_1/P_0	P_{1+0}, d	P_{1-0}, d
1	0.395196	0.529664	2455000.332	2455000.237	0.7461	–	–
2	0.420513	0.564048	2455000.275	2455000.250	0.7455	0.240908	–
3	0.357769	0.480781	2455000.023	2455000.148	0.7441	0.2051257	1.39816
4	0.418642	0.561570	2455000.406	2455000.035	0.7455	0.2398406	1.6450
5	0.356657	0.479216	2455000.248	2455000.414	0.7443	–	–
6	0.371362	0.498566	2455000.240	2455000.335	0.7449	0.212834	1.45553
7	0.350894	0.472146	2455000.542	2455000.636	0.7432	0.201293	–
8	0.358253	0.481136	2455000.062	2455000.200	0.7446	0.205350	1.40272
9	0.376512	0.505835	2455000.245	2455000.107	0.7443	0.215849	1.47280
10	0.359741	0.482865	2455000.095	2455000.370	0.7450	–	–
11	0.356102	0.478487	2455000.337	2455000.235	0.7442	–	–
12	0.364073	0.489181	2455000.358	2455000.336	0.7443	0.20873	1.4234
13	0.355872	0.478181	2455000.037	2455000.374	0.7442	0.204029	1.3912
14	0.404849	0.542956	2455000.070	2455000.087	0.7456	0.231921	1.59165
15	0.379178	0.509437	2455000.256	2455000.007	0.7443	0.217380	1.48303
16	0.375307	0.503529	2455000.277	2455000.423	0.7454	0.215033	1.47384
17	0.388921	0.521624	2455000.140	2455000.023	0.7456	–	–

Table 2. Light elements (continued)

No.	P_1, d	P_0, d	Epoch$_1$, JD	Epoch$_0$, JD	P_1/P_0	P_{1+0}, d	P_{1-0}, d
18	0.395859	0.530969	2455000.092	2455000.210	0.7455	0.226780	1.55578
19	0.354037	0.475673	2455000.165	2455000.205	0.7443	–	–
20	0.374572	0.502380	2455000.260	2455000.287	0.7456	–	–
21	0.408675	0.548171	2455000.454	2455000.486	0.7455	0.234125	–
22	0.350447	0.471002	2455000.082	2455000.224	0.7440	0.200940	–
23	0.420090	0.563212	2455000.142	2455000.235	0.7459	0.240616	–
24	0.363631	0.488334	2455000.047	2455000.148	0.7446	0.2084305	–
25	0.358410	0.481418	2455000.231	2455000.005	0.7445	0.2054526	–
26	0.413009	0.553220	2455000.221	2455000.350	0.7466	–	–
27	0.364671	0.489470	2455000.258	2455000.375	0.7450	–	1.43026
28	0.346374	0.465896	2455000.014	2455000.093	0.7435	–	–
29	0.358597	0.481845	2455000.290	2455000.285	0.7442	0.2055945	1.40187
30	0.408059	0.547015	2455000.335	2455000.330	0.7460	0.2337154	–
31	0.351155	0.472132	2455000.145	2455000.464	0.7438	–	–
32	0.361440	0.485546	2455000.285	2455000.040	0.7444	–	–
33	0.364224	0.488888	2455000.150	2455000.295	0.7450	0.208724	–
34	0.370019	0.496630	2455000.047	2455000.283	0.7451	0.212040	1.4515
35	0.369046	0.495555	2455000.125	2455000.163	0.7447	–	–
36	0.345262	0.464667	2455000.199	2455000.037	0.7430	0.1980798	–
37	0.354717	0.476683	2455000.236	2455000.012	0.7441	0.2033766	–
38	0.354417	0.476173	2455000.150	2455000.170	0.7443	0.203186	–
39	0.356490	0.478545	2455000.355	2455000.097	0.7449	–	–
40	0.407076	0.546206	2455000.385	2455000.027	0.7453	0.233251	1.5980
41	0.357291	0.480226	2455000.357	2455000.185	0.7440	–	–
42	0.411982	0.552328	2455000.287	2455000.520	0.7459	–	–
43	0.373998	0.502498	2455000.224	2455000.111	0.7443	0.214413	–
44	0.401141	0.537739	2455000.302	2455000.240	0.7460	0.229749	1.57949
45	0.364808	0.489858	2455000.194	2455000.492	0.7447	0.209094	1.42901
46	0.374442	0.502028	2455000.310	2455000.100	0.7459	0.214475	–
47	0.355820	0.478308	2455000.328	2455000.100	0.7439	0.204035	–
48	0.406224	0.544770	2455000.285	2455000.248	0.7457	0.2327005	–
49	0.407067	0.545923	2455000.375	2455000.240	0.7456	–	–
50	0.402699	0.539620	2455000.410	2455000.333	0.7463	0.230605	1.58705
51	0.388810	0.521470	2455000.155	2455000.331	0.7456	0.222735	–
52	0.357748	0.480465	2455000.080	2455000.147	0.7446	0.205062	1.4008
53	0.356073	0.478391	2455000.170	2455000.006	0.7443	0.204134	–
54	0.371521	0.498880	2455000.205	2455000.165	0.7447	0.212939	–
55	0.349286	0.469896	2455000.237	2455000.026	0.7433	0.2003575	–
56	0.366862	0.492663	2455000.222	2455000.396	0.7447	0.210279	1.4368

Table 3 presents semi-amplitudes of all the oscillations, separately for Catalina surveys 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. Table 4 presents semi-amplitudes of all the oscillations, separately for SuperWASP data.

Table 3. Semi-amplitudes (CSS data)

No.	A_1	A_0	A_{1+0}	A_{1-0}	No.	A_1	A_0	A_{1+0}	A_{1-0}
1	0.177	0.102	–	–	29	0.131	0.132	0.053	0.032
2	0.153	0.048	0.030	–	30	0.137	0.086	0.038	–
3	0.175	0.136	0.058	0.027	31	0.182	0.117	–	–
4	0.149	0.078	0.036	0.035	32	0.178	0.115	–	–
5	0.144	0.078	–	–	33	0.155	0.066	0.029	–
6	0.162	0.081	0.034	0.030	34	0.163	0.082	0.051	0.036
7	0.130	0.123	0.043	–	35	0.144	0.064	–	–
8	0.159	0.094	0.032	0.027	36	0.174	0.085	0.055	–
9	0.158	0.115	0.055	0.022	37	0.149	0.134	0.051	–
10	0.188	0.071	–	–	38	0.158	0.123	0.045	–
11	0.183	0.067	–	–	39	0.146	0.083	–	–
12	0.168	0.139	0.075	0.057	40	0.147	0.088	0.036	0.046
13	0.164	0.123	0.041	0.022	41	0.153	0.110	–	–
14	0.139	0.089	0.034	0.034	42	0.135	0.065	–	–
15	0.155	0.066	0.026	0.025	43	0.173	0.073	0.030	–
16	0.176	0.087	0.042	0.029	44	0.143	0.083	0.042	0.034
17	0.139	0.084	–	–	45	0.153	0.138	0.054	0.047
18	0.158	0.120	0.036	0.039	46	0.160	0.046	0.022	–
19	0.185	0.114	–	–	47	0.144	0.100	0.047	–
20	0.164	0.082	–	–	48	0.170	0.044	0.022	–
21	0.165	0.060	0.029	–	49	0.146	0.081	–	–
22	0.179	0.091	0.039	–	50	0.130	0.029	0.027	–
23	0.143	0.070	0.049	–	51	0.134	0.065	0.037	–
24	0.169	0.100	0.055	–	52	0.171	0.070	0.027	–
25	0.162	0.125	0.048	–	53	0.147	0.087	0.027	–
26	0.172	0.081	–	–	54	0.172	0.083	0.042	–
27	0.164	0.068	–	0.029	55	0.147	0.102	0.046	–
28	0.174	0.127	–	–	56	0.150	0.106	0.058	–

Table 4. Semi-amplitudes (SuperWASP data)

No.	A_1	A_0	A_{1+0}	A_{1-0}
50	0.126	0.055	0.025	0.019
52	0.143	0.075	0.026	0.019
56	0.110	0.081	0.039	0.029

Comments:

7. The star has a faint close red companion USBO-B1.0 1211-0158002, $d = 1\farcs5$, visible only in DSS images in the red and infrared bands.

13. In USNO-B1.0 catalog, two entries correspond to one star: USNO-B1.0 1265-0169434 and USNO-B1.0 1265-0169435; the coordinates in the first entry are more accurate.

35. The star has a faint close companion USNO-B1.0 0997-0233329, $d = 6\farcs7$; the measured amplitudes can be somewhat underestimated.

42. In DSS images, the star USNO-B1.0 0965-0243978 is noticeably elongated; possibly it is a close pair, $d < 1''$, unresolved in the catalogs. The faint companion is located to the west. Combined brightness of the two stars was measured in the CSS data; the measured amplitudes can be somewhat underestimated.

50. CSS data are for brightness of two stars, GSC2.3 N09A000095 and GSC2.3 N09A009350, $d = 5\farcs5$. This pair is unresolved in the CSS data and in the GSC catalog (GSC 2222-02434). Most likely, the brighter star of the pair, GSC 2.3 N09A000095, varies. This pair is unresolved in the 1SWASP; the measured amplitudes can be somewhat underestimated. From 1SWASP data, $14\fm9 - 15\fm5$.

51. The star has a faint close companion GSC2.3 N0OD009449 (=USNO-B1.0 1016-0656704), $d = 4\farcs9$; the measured amplitudes can be somewhat underestimated.

52. From 1SWASP data, $14\fm52 - 15\fm20$. In 1SWASP data, the measured amplitudes possible can be somewhat underestimated because of the neighbor, USNO-B1.0 1233-0612342, $d = 23''$.

56. From 1SWASP data, $13\fm50 - 14\fm10$. In 1SWASP data, the measured amplitudes can be somewhat underestimated because of the neighbor, GSC 2255-00823, $d = 41''$.

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