USNO-B1.0 1171-0309158: An RR Lyrae Star that Switched from a Double- to Single-mode Pulsation

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ABSTRACT

We report the discovery of a new case of an RR Lyrae star that experienced a switching of its pulsation mode. We detected USNO-B1.0 1171-0309158 as a double-mode RR Lyrae star from observations of the Catalina surveys (CSS) that showed additional scattering on the light curve. Our analysis of the time-series of CSS data showed gradual increase in scattering and in the amplitude of fundamental pulsation mode. Our CCD observations carried out in 2015 reveal that this object is now a fundamental-mode RRab star, with no sign of the first-overtone pulsation.

Key words: Stars: variables: RR Lyrae - Stars: oscillations - Stars: Population II - Stars: horizontal-branch

1. Introduction

RR Lyrae stars are known to normally keep their pulsation mode unchanged. Until recently, only one case of an RR Lyrae star that changed its pulsation mode was known, V79 in the globular cluster M3 (Kaluzyv et al. 1998, Goranskij et al. 2010). In 2014, four more stars of this type were detected using data of the Optical Gravitational Lensing Experiment (OGLE-III and OGLE-IV). Three of these stars are in Galactic bulge fields OGLE-BLG-RRLYR-12245 (Soszynski et al. 2014a), OGLE-BLG-RRLYR-07226 and OGLE-BLG-RRLYR-13442 (Soszynski et al. 2014b), and one star is in the Large Magellanic Cloud, OGLE-LMC-RRLYR-13308 (Poleski 2014). Besides, Drake et al. (2014) announced the discovery of six mode-changing RR Lyr stars in the sample observed by the Catalina surveys; however, these cases need confirmation. In this paper, we report the discovery of a new case of an RR Lyrae star that experienced a switching of its pulsation mode.
Among the five previously known RR Lyrae stars that experienced a switching of their pulsation mode, there are three cases of RR(B) → RRab change (of which, one case is in the LMC); two cases are RRab → RR(B) (of which, one case is in a globular cluster, V79/M3). For double-mode RR Lyrae stars (mainly pulsating in the fundamental and first overtone modes, F/1O), we use designation RR(B), according to the General Catalogue of Variable Stars (Samus et al. 2007 – 2015), equivalent to the widely used designation RRd. In all cases, the single-mode pulsation is that in the fundamental mode (type RRab). Mode-switching of the RRc → RR(B) or RR(B) → RRc type (the single-mode pulsation being that in the first overtone mode) is not known. In this paper, we report the discovery of a new (sixth) case of a mode-switching RR Lyrae star.

We performed a search for double-mode variable stars using several available photometric surveys. In the course of the analysis of the Catalina Sky Survey data (CSS, Drake et al. 2009), we detected double-mode variability for more than 200 stars (Khruslov 2014, 2015ab). Using these data, we 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). Based on our results and other information available for RR(B) stars, we plotted the period distribution for the Galactic-field double-mode RR Lyrae stars (Khruslov 2015c). Earlier, the double-peaked character of the period distribution for Galactic RR(B) stars was not obvious. We have suggested that this distribution can be related to the Oosterhoff’s classes I and II for RR Lyrae stars in globular clusters. In the search for RR Lyrae variables with two radial pulsations, we detected double-mode periodicity of USNO-B1.0 1171-0309158.

The variability of USNO-B1.0 1171-0309158 = CSS_J165642.0+270955 (α = 16h56m41.98, δ = +27°09′55″.1, J2000.0, in the 2MASS catalog, Skrutskie et al. 2006) was reported by Drake et al. (2014) in the Catalina surveys periodic variable star catalog. The variable was classified as an RR Lyrae star (RRc sub-type) with the period 0.38421 days. We reinvestigated the star using the Catalina Surveys data and detected its double-mode variability. In May, 2015, we started our dedicated observations of the star. Later, independently from us, the double-mode periodicity of CSS_J165642.0+270955 was detected by P. Wils, who reported it on December 2, 2015 to the International Variable Stars Index, AAVSO.

2. Analysis of the CSS observations

According to CSS data, USNO-B1.0 1171-0309158 is a double-mode RR Lyrae star, pulsating in the fundamental and first overtone modes (F/1O). However, the phased light curve showed a slightly larger scattering compared to other double-mode stars. It suggested that the period varied. To test this assumption, we ana-
alyzed the CSS data in two time intervals using Deeming’s method (Deeming 1975) implemented in the WinEfk code written by V.P. Goranskij.

The analysis of the first half of the time-series (JD2453470 – 2455000) showed a stable double periodicity without additional scattering in the phased light curve. The analysis of the second half of the time-series (JD2455000 – 2456590) showed a double periodicity with additional large scattering in the phased light curve.

Table 1

<table>
<thead>
<tr>
<th>Time interval</th>
<th>JD2453470 – 2455000</th>
<th>JD2455000 – 2456590</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>fundamental mode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(P_0), days</td>
<td>0.516675</td>
<td>0.516734</td>
</tr>
<tr>
<td>(E_{epoch_0}), HJD</td>
<td>2454200.184</td>
<td>2455800.322</td>
</tr>
<tr>
<td>Semi-amplitude (A_0)</td>
<td>0.083</td>
<td>0.158</td>
</tr>
<tr>
<td><strong>first overtone mode</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(P_1), days</td>
<td>0.384216</td>
<td>0.384144</td>
</tr>
<tr>
<td>(E_{epoch_1}), HJD</td>
<td>2454200.342</td>
<td>2455800.170</td>
</tr>
<tr>
<td>Semi-amplitude (A_1)</td>
<td>0.155</td>
<td>0.112</td>
</tr>
<tr>
<td><strong>period ratio</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(P_1/P_0)</td>
<td>0.7436</td>
<td>0.7434</td>
</tr>
</tbody>
</table>

In the second half of the time-series, the amplitude of the fundamental mode increased significantly (almost by a factor of 2); the amplitude of the first overtone mode decreased slightly. The fundamental mode period increased by \(\Delta P_0 = 0^d.000059 \approx 5\) s; the first overtone period decreased by \(\Delta P_1 = 0^d.000072 \approx 6\) s.

The light curves in the first and second time intervals are displayed in Figs. 1 and 2. Along with the light curves, we present power spectra, for the raw data and after subtraction of the first overtone mode oscillations. The variability ranges in the CSS data are \(15''73 - 16''59 \) (CV). The change of amplitude of the fundamental mode pulsation (after subtraction of the first overtone mode oscillations) for full interval of CSS observations is displayed in Fig. 3.

We find that pulsations in the first overtone mode completely ended; after mode-switching, USNO-B1.0 1171-0309158 became an RRab star.

3. CCD observations

To confirm the mode-switching of USNO-B1.0 1171-0309158, we started CCD observations in May 2015. Our CCD observations in the Johnson B, V and R bands were performed at the Tien Shan Astronomical Observatory of the V.G. Fesenkov Astrophysical Institute, at the altitude of 2750 m above the sea level. The observatory has two Zeiss 1000-mm telescopes. All our observations were performed with the eastern Zeiss 1000-mm reflector (the focal length of the system was \(f = 6650\) mm; the detector was an Apogee U9000 D9 CCD camera; the chip was cooled to \(-40^\circ\) C). The time interval of the observations for USNO-B1.0 1171-0309158
Fig. 1. Light curves and power spectra of USNO-B1.0 1171-0309158 according to CSS data, JD 2453470 – 2455000. The light curves in upper panels: raw data; those in the lower panels: the folded light curves with the other oscillation pre-whitened. Under the light curves, we present power spectra, for the raw data and after subtraction of the dominant oscillation.

Information on the comparison stars and check stars, used in our CCD photometry, is presented in Table 2. Magnitudes of the comparison stars (in Johnson’s B and V bands) were taken from the AAVSO Photometric All-Sky Survey (APASS) catalog. The R-band observations could be presented only as magnitude differences with respect to the comparison star. ΔR: ΔR = m_{var} - m_{comp} - 1^m.790. The finding chart is displayed in Fig. 4.

http://www.aavso.org/download-apass-data
Fig. 2. Light curves and power spectra of USNO-B1.0 1171-0309158 according to CSS data, JD 2455000 – 2456590.

Our CCD observations completely confirmed our assumptions: in 2015, in the JD2457161 – 2457259 time interval, USNO-B1.0 1171-0309158 was pulsat-
ing only in the fundamental mode, the amplitude and the shape of the light curve corresponded to the RRab type, and first overtone oscillations were not detected.

The light curves in the $B$, $V$ and $R$ bands are shown in Fig. 5. In the time interval of our CCD observations, the light elements were:

$$\text{HJD (max)} = 2457209.290 + 0^{d}.51722 \times E.$$  

The variability ranges in different bands are: $15''.72 - 17''.28$ in the $B$ band, $15''.57 - 16''.83$ in the $V$ band; the full amplitude in the $R$ band is $1'''.02$. The

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Comparison and check stars</th>
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</thead>
<tbody>
<tr>
<td><strong>Comparison star</strong></td>
<td>Name</td>
</tr>
<tr>
<td>Coordinates, J2000.0</td>
<td>$16^h 56^m 40^s.43 +27^\circ 08' 44''.0$</td>
</tr>
<tr>
<td>$V$ mag</td>
<td>14.083</td>
</tr>
<tr>
<td>$B$ mag</td>
<td>14.730</td>
</tr>
<tr>
<td><strong>Check star</strong></td>
<td>Name</td>
</tr>
<tr>
<td>Coordinates, J2000.0</td>
<td>$16^h 56^m 41^s.08 +27^\circ 09' 58''.0$</td>
</tr>
</tbody>
</table>
durations of light increase from minimum to maximum $M - m = 0^{P}.13$.

![Light curve diagram](image)

$HJD(\text{max}) = 2457209.290 + 0.51722 \times E$

Fig. 5. The light curves of USNO-B1.0 1171-0309158 in the $B$, $V$ and $R$ bands according to CCS observations, JD2457161 – 2457259.

4. Conclusions

In the search for RR Lyrae variables with two radial pulsation in the Catalina Surveys data, we first detected double-periodicity and then mode-switching of USNO-B1.0 1171-0309158. The mode-switching is confirmed by our CCD observations. The star changed its type from RR(B) to RRab.

In the time interval of observations (CSS and our CCD data, JD2453470 – 2457260), the period of USNO-B1.0 1171-0309158 changed by $\Delta P_0 = 0^d.000545 \approx 47$ s. This amount is close to those for OGLE-BLG-RRLYR-12245 ($\Delta P_0 = 0^d.000489 \approx 42$ s) and OGLE-LMC-RRLYR-13308 ($\Delta P_0 = 0^d.000565 \approx 49$ s), where it is less than one minute. However, OGLE-BLG-RRLYR-07226 ($\Delta P_0 = 0^d.002242 \approx 3.2$ min) and V79/M3 ($\Delta P_0 = \pm 0^d.00381 \approx \pm 5.5$ min) experienced larger period changes. In the case of OGLE-BLG-RRLYR-13442, the period change is smaller, $\Delta P_0 = -0^d.000128 = -11$ s.

USNO-B1.0 1171-0309158 in the Petersen diagram are displayed in Fig. 6.
Fig. 6. The Petersen diagram for the Galactic field double-mode RR Lyrae F/1O variables. Filled squares represent the known RR(B) stars; empty squares represent the OGLE RR(B) stars; the empty circle is USNO-B1.0 1171-0309158 in the time range of CSS observations.

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REFERENCES

Khruslov, A. V. 2015c, Baltic Astronomy, 24, 379.

