Possible Evidence of Hydrogen Emission in the First-overtone and Multimode RR Lyrae Variables

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Abstract

The nature of shock waves in nonfundamental mode RR Lyrae stars remains a mystery because of limited spectroscopic observations. We apply a pattern recognition algorithm on spectroscopic data from SDSS and LAMOST and report the first evidence of hydrogen emission in first-overtone (RRc) and multimode (RRd) RR Lyrae stars showing the “first apparition,” which is the most prominent observational characteristic of shock in RR Lyrae variables. We find 10 RRc stars in SDSS, 10 RRc stars in LAMOST, and 3 RRd stars in LAMOST that show blueshifted Balmer emissions. The emission features possibly indicate the existence of shock waves. We calculate the radial velocities of the emission lines, which are related to the physical conditions occurring in the radiative zone of shock waves. Using photometric observations from ZTF, we present a detailed light-curve analysis for the frequency components in one of our RRd stars with hydrogen emission, RRd13, for possible modulations. With the enormous volume of upcoming spectral observations of variable stars, our study raises the possibility of connecting the unexplained Blazhko effect to shock waves in nonfundamental mode RR Lyrae stars.

Unified Astronomy Thesaurus concepts: RR Lyrae variable stars (1410); RRc variable stars (1415); RRd variable stars (1876); Shocks (2086); Blazhko effect (2110); Stellar atmospheres (1584); Stellar atmospheric opacity (1585); Pulsation modes (1309); Stellar pulsations (1625); Spectroscopy (1558); Astronomy data analysis (1858); Astronomy databases (83)

1. Introduction

The most intriguing observational property of RR Lyrae stars is that some of them show periodic amplitude and/or phase modulations, named the “Blazhko effect” (Blazhko 1907). The light curves of these stars are modulated on timescales of tens to hundreds of days. The mechanism that causes the Blazhko effect is still under debate.

There have been several proposed hypotheses to explain the Blazhko effect. Shibahashi (2000) interpreted the Blazhko effect by an oblique dipole magnetic rotator model. The lack of strong magnetic fields in the photosphere of Blazhko RR Lyrae stars disproved this explanation (Chadid et al. 2004). Buchler & Kolláth (2011) demonstrated that irregular amplitude modulations can be triggered naturally by the nonlinear, resonant mode coupling between the fundamental mode and the ninth overtone. Stothers (2010, 2011) proposed that turbulent envelope convective cycles induce the modulations. Chadid et al. (2010, 2011) first presented extensive photometry from space and detected significant cycle-to-cycle changes in the Blazhko modulation, which appear to be analogous to the predictions by Stothers.

Moreover, Chadid et al. (2014) proposed that the origin of the Blazhko effect is a dynamical interaction between a multishock structure and an outflowing wind in a coronal structure. The authors discovered multishocks propagating through the atmospheres of RR Lyrae stars through very complicated features in the RR Lyrae light curves, including jump, lump, rump, bump, and hump, all characterized by various amplitudes and origins.

At the Blazhko phase minimum, the Blazhko amplitude is at the minimum, the rise time is at the maximum, the shock intensity is smaller, the amplitude of the bump is lower, and the star roughly looks like an RRc. Whereas at the Blazhko phase maximum, the Blazhko amplitude is at the maximum, the rise time is at the minimum, the shock intensity is higher, the amplitude of the bump is stronger, and the light curve of the Blazhko star is similar to an RRab.

In order to study the dynamics of shock waves in the atmosphere of RR Lyrae, we can trace the observational characteristics of the spectra. Propagation of shock waves through the stellar atmosphere leads to hydrogen emission lines, helium emission lines, line broadening and doubling phenomena, and neutral metallic line disappearance phenomena in RR Lyrae stars (Iroshnikov 1962; Chadid et al. 2008, 2017). However, these phenomena were not found in all types of RR Lyrae. RR Lyrae stars can be classified by their pulsations as fundamental mode (RRab), first overtone (RRc), or multimode (RRd) RR Lyrae according to the number of oscillation modes (Soszyński et al. 2016; Beaton et al. 2018; Bhardwaj 2020). As for RRab stars, three moderate-to-weak hydrogen emission lines, named “three apparitions,” appear sequentially in the spectra during a pulsation cycle (Preston 2011). The “first apparition” is a blueshifted emission line, generated when the shock wave is close to the photosphere, indicating the coming of the maximum luminosity. The “second apparition” is a weak hump at the blue emission shoulder of Hα, which appears during the preeminium brightening near φ = 0.7. This weak hump is thought to be produced by
photometric and spectroscopic observations. Time-domain photometry was used to identify the types of RR Lyrae stars, which were retrieved from the open resources of the Catalina Sky Survey (Drake et al. 2014, 2017), Gaia DR2 (Clementini et al. 2019), Wide-field Infrared Survey Explorer (WISE; Chen et al. 2018), All-Sky Automated Survey for Supernovae (ASAS-SN; Jayasinghe et al. 2019), and Asteroid Terrestrial-impact Last Alert System (ATLAS; Heinze et al. 2018). After combining these catalogs and removing duplicate data we get 68,152 RR Lyrae stars. We also get light curves from the Zwicky Transient Facility (ZTF; Bellm et al. 2019; Chen et al. 2020) for our selected stars if available.

We search for the “first apparitions” among low-resolution and single-epoch spectra from the Sloan Digital Sky Survey (SDSS; Eisenstein et al. 2011) and the Large Sky Area Multi-Object Fiber Spectroscopic Telescope survey (LAMOST; Deng et al. 2012). Due to the fact that periods of RR Lyrae stars are rather short, and the “first apparition” only enjoys about 5% of the whole pulsation cycle (Chadid 2011), long-time exposures and the coaddition of spectra smooth out the relevant emission lines. In both SDSS and LAMOST surveys, each plate (sky pointing) was observed three times, 10–20 minutes each for SDSS and 25 minutes each for LAMOST. This gives the best possible time resolution for variable targets, which turns out to be good enough for our purpose of studying RR Lyrae stars. Some of the SDSS spectra come from BOSS. Spectra of SDSS cover the wavelength from 3800–9200 Å and those of BOSS have a wavelength coverage of 3650–10400 Å. Both data provide resolutions of 1500 at 3800 Å and 2500 at 9000 Å. We choose the “spcFrame” spectra, which achieve nominal resolutions of about 4150 at Hα and 4180 at Hβ. In the data set of LAMOST DR6, the spectral coverage is from 3550–9110 Å with R ~ 1800, the nominal resolutions are about 7800 at Hα and 8400 at Hβ. After pair-matching the catalogs using TOPCAT (Taylor et al. 2005), we retrieve RR Lyrae stars 3526 from SDSS DR7–9 and 5571 from LAMOST DR1–6. All selected targets have both light curves and spectra.

To hunt for the “first apparitions,” the common practice is to visually check the profiles of hydrogen Balmer lines for any sign of emission in a small sample. For large survey data, this can become an enormous amount of work. Therefore, we build a pipeline using a handcrafted one-dimensional pattern recognition method. We presuppose the pattern of the “first apparition” as a Gaussian-like emission profile on the blue wing of a broad Gaussian-like absorption profile when both signals are more significant than 2σ compared to the average level. We assume that the minimum flux value in the selected windows (e.g., 6540–6590 Å for Hα) indicates the location of the Balmer absorption profile. We retain the results of the hunt that show clear patterns of the “first apparition” in Hα and Hβ simultaneously and that include at least two observational points on the profiles of emission. We apply the pipeline to the spectra of RR Lyrae stars from SDSS and LAMOST, with visual inspection to check for a false negative.

The components of emission and absorption are fitted based on the scale width versus shape method for the Balmer lines (Sersic 1968; Clewley et al. 2002). We adopt two Sérsic profiles (Xue et al. 2008; Yang et al. 2014) as:

\[ y = m - ae^{-\left(\frac{\text{FWHM}}{2}\right)^2}, \]

(1)

to fit the profile and measure the flux, intensity, and full width at half maximum (FWHM) for the two components. Uncertainties are generated by error propagation using the covariance matrix and Monte Carlo method (Andrae 2010).

3. Results

As one of the main results of the search, we find 10 RRc stars in SDSS, 10 RRc stars in LAMOST, and 3 RRd stars in LAMOST that show shifted emission components on the blue wing of the Balmer absorption lines. The spatial distribution of those RR Lyrae is shown in Figure 1. Figures 2 and 3 show the SDSS and LAMOST spectra, respectively, which display the feature in the Hα line. The reference frame for the wavelength axis is the stellar rest frame. The flux is normalized by the continuum. The blueshifted Hα emission lines are shown as pink profiles. The Hβ profiles are displayed in the subplots. We
calculate the significance of the emission lines as the signal-to-noise ratio (S/N). We choose the candidates with the signals of Hα exceeding 2σ and the signals of Hβ exceeding 1σ.

The significances of the emission lines certify their physical reality. Moreover, the probability that the spectra show significant signals at Hα and Hβ at the same time due to the statistical effects of noise is close to zero. The correlation between emission and absorption features appears to distort the location of their centroids. There are slight differences between the redshifts given by the centroids of the absorption lines and given by the SEGUE Stellar Parameter Pipeline (SSPP; Lee et al. 2008) or the LAMOST stellar parameter pipeline (LASP; Wu et al. 2014) in some stars. We display examples of the evolution of the Hα and Hβ line profiles of RRc in SDSS and LAMOST and RRd in LAMOST in Figure 4. To avoid the miscalculation of the phase due to the Blazhko effect, we only present the differences of phases. The emission lines are gradually getting intenser or weaker, which indicates that the signals are real evolving emissions instead of coincidences due to noise.

Three RRc stars in LAMOST show blueshifted Balmer emissions in multiple spectra of a single plane, whereas no such candidates are found in SDSS, possibly due to our strict selection criteria. We also get no RRd stars with “first apparitions” in SDSS. We find two RRd stars in SDSS that may contain the emission feature, but we reject them because there is only one observational point on the emission profile.

Parameters of the stars and measurements of the emission lines are summarized in Tables 1 and 2. We collect parameters generated by SSPP, LASP, and Liu et al. (2020). As for SSPP and LASP, these two pipelines also report primary stellar parameters such as effective temperature (T\textsubscript{eff}), surface gravity (log g), and their uncertainties for most stars in the temperature range 4000–10,000 K, with spectral S/Ns exceeding 10. Liu et al. (2020) adopted a new method to measure the metallicities of RR Lyrae stars. Considering the nature of pulsating stars, they provided measurements for individual single-epoch spectra and adopted mean values weighted by S/N as the final metallicity to avoid the influence from the “apparitions.” They
Figure 3. As in Figure 2, but for RRc and RRd stars, which show shock wave observational characteristics in LAMOST.
fixed the δ-element to iron abundance ratio, [α/Fe], to 0.4, which causes their measurement result to be more sensitive for metal-poor stars than LASP but to suffer from larger uncertainties than SSPP, so we adopt it for the LAMOST data set. For the emission component of the “first apparition,” we also measure the redshift in the frame of the observer, radial velocity in the stellar rest frame, normalized flux, and FWHM.

Figure 4. Evolution of the Hα and Hβ line profiles of RRcs8, RRcl2, and RRd12. The frame of reference for the wavelength axis is the stellar rest frame. The vertical red lines indicate the Hα line laboratory wavelength, while the vertical blue lines indicate the Hβ line laboratory wavelength.

Table 1
Parameters of Selected RRc and RRd Stars from the SDSS and LAMOST Samples

### RRc Stars from the SDSS Sample

| Object | R.A.(J2000) (°) | Decl.(J2000) (°) | Period (day) | V (mag) | Amp (mag) | z^s | T_eff (K) | log g^s | [Fe/H] |
|--------|----------------|-----------------|-------------|--------|----------|-----|----------|--------|-------|
| RRc1   | 198.35858      | +18.16208       | 0.33851     | 16.78  | 0.42     | −2.05E − 4±1.69E − 5 | 7626.91 ± 99.38 | 3.56 ± 0.37 | −1.79 ± 0.05 |
| RRc2   | 174.79487      | +18.36381       | 0.34043     | 16.88  | 0.35     | 2.17E − 4±1.49E − 5 | 6783.39 ± 78.43 | 2.82 ± 0.18 | −1.69 ± 0.02 |
| RRc3   | 210.54617      | −3.02092        | 0.32518     | 17.31  | 0.53     | 4.95E − 4±1.11E − 5 | 7443.48 ± 138.66 | 3.71 ± 0.26 | −1.63 ± 0.16 |
| RRc4   | 221.99438      | +3.47414        | 0.35448     | 17.37  | 0.36     | −6.13E − 4±1.19E − 5 | 7394.68 ± 38.43 | 3.28 ± 0.40 | −1.61 ± 0.06 |
| RRc5   | 246.94200      | +20.78986       | 0.32556     | 17.41  | 0.36     | −5.53E − 4±2.22E − 5 | 7065.13 ± 58.53 | 3.05 ± 0.23 | −1.26 ± 0.07 |
| RRc6   | 189.85158      | +49.18964       | 0.37950     | 17.55  | 0.43     | 1.32E − 4±3.06E − 5 | 6978.94 ± 158.95 | 3.30 ± 0.68 | −2.33 ± 0.01 |
| RRc7   | 155.54754      | +45.33461       | 0.38524     | 17.62  | 0.37     | −5.12E − 4±1.43E − 5 | 6982.75 ± 86.32 | 2.94 ± 0.16 | −2.06 ± 0.03 |
| RRc8   | 41.93854       | +0.60214        | 0.28773     | 17.73  | 0.47     | −5.56E − 4±1.92E − 5 | 7241.95 ± 56.80 | 3.25 ± 0.36 | −1.57 ± 0.08 |
| RRc9   | 198.54504      | +3.55614        | 0.39695     | 17.97  | 0.48     | 6.44E − 5±1.40E − 5 | 7245.77 ± 98.90 | 3.05 ± 0.52 | −2.51 ± 0.10 |
| RRc10  | 189.62392      | +0.33389        | 0.35529     | 18.63  | 0.36     | 4.96E − 5±1.20E − 5 | /         | /        | −1.92 ± 0.23 |

### RRc and RRd Stars from the LAMOST Sample

| Object | R.A.(J2000) (°) | Decl.(J2000) (°) | Period (day) | V (mag) | Amp (mag) | z^L | [Fe/H] |
|--------|----------------|-----------------|-------------|--------|----------|-----|-------|
| RRe1   | 247.04771      | 9.45261         | 0.32534     | 14.91  | 0.41     | −8.53E − 4±1.65E − 6 | −1.41 ± 0.09* |
| RRe2   | 221.59958      | −0.11594        | 0.32560     | 14.92  | 0.35     | −4.30E − 4±2.27E − 5 | −1.57 ± 0.10* |
| RRe3   | 169.58008      | −4.83961        | 0.35061     | 15.41  | 0.42     | 9.39E − 4±6.88E − 5 | /         |
| RRe4   | 58.24550       | +29.20903       | 0.33122     | 15.53  | 0.35     | 3.80E − 4±5.37E − 5 | −1.68 ± 0.14* |
| RRe5   | 344.53867      | +0.87136        | 0.28274     | 15.82  | 0.39     | −9.43E − 4±5.60E − 5 | −1.30 ± 0.14* |
| RRe6   | 173.43429      | −5.10247        | 0.31021     | 15.86  | 0.36     | 4.39E − 4±3.10E − 5 | −1.65 ± 0.25* |
| RRe7   | 76.40079       | −2.05489        | 0.36290     | 16.26  | 0.32     | 6.22E − 4±6.00E − 6 | /         |
| RRe8   | 44.33796       | −0.22086        | 0.30943     | 16.77  | 0.30     | −1.96E − 4±1.16E − 5 | −1.29 ± 0.25* |
| RRe9   | 206.81642      | +52.56544       | 0.41721     | 16.81  | 0.41     | −9.41E − 4±4.98E − 6 | /         |
| RRe10  | 236.50104      | +24.13336       | 0.29025     | 17.03  | 0.33     | −1.02E − 3±7.48E − 5 | /         |
| RRe11  | 266.95863      | +24.17853       | 0.57764     | 14.93  | 0.77     | −8.12E − 4±1.91E − 5 | −2.18 ± 0.09* |
| RRe12  | 233.10042      | +41.47511       | 0.38228     | 15.61  | 0.39     | −6.83E − 4±2.12E − 5 | /         |
| RRe13  | 223.47962      | +39.53931       | 0.35499     | 15.81  | 0.33     | −9.47E − 4±8.73E − 6 | −1.50 ± 0.20* |

Notes.
1. Period, V, and Amp (Amplitude) are produced by Catalina Sky Survey.
2. z^s, T_eff, log g^s, and [Fe/H] (without *) are generated from SSPP. z^L is generated from LASP.
3. [Fe/H] with * are given by Liu et al. (2020). [Fe/H] of RRc10 is lack of data in SSPP.
4. Unavailable values are marked using a backslash /.
# Table 2
Measurements of Selected RRc and RRd Stars from the SDSS and LAMOST Samples

| Object       | $z_{e1,o}$     | $V_{e1,o}$  | Flux$_{e1,o}$ | FWHM$_{e1,o}$ |
|--------------|----------------|-------------|--------------|---------------|
| RRc81       | $-9.44E-4 \pm 1.87E-4$ | $-195 \pm 79$ | 0.30         | 3.33          |
| RRc82       | $-1.97E-4 \pm 1.88E-4$ | $-93 \pm 44$  | 0.24         | 2.83          |
| RRc83       | $1.13E-4 \pm 1.88E-4$  | $-94 \pm 59$  | 0.24         | 2.57          |
| RRc84       | $-8.97E-4 \pm 1.87E-4$ | $-106 \pm 61$ | 0.30         | 3.17          |
| RRc85       | $-1.09E-4 \pm 3.17E-4$ | $-194 \pm 70$ | 0.22         | 2.59          |
| RRc86       | $-3.06E-4 \pm 1.88E-4$ | $-106 \pm 73$ | 0.25         | 4.92          |
| RRc87       | $-9.10E-4 \pm 1.19E-4$ | $-70 \pm 39$  | 0.39         | 3.39          |
| RRc88       | $-8.97E-4 \pm 1.87E-4$ | $-86 \pm 78$  | 0.59         | 3.87          |
| RRc90       | $-3.98E-4 \pm 1.87E-4$ | $-92 \pm 62$  | 0.33         | 1.89          |
| RRc91       | $-5.59E-4 \pm 1.66E-4$ | $-165 \pm 59$ | 0.40         | 3.04          |
| RRc1115     | $-1.22E-3 \pm 7.41E-5$ | $-137 \pm 22$ | 0.15         | 4.09          |
| RRc122      | $-1.14E-3 \pm 9.90E-5$ | $-70 \pm 25$  | 0.20         | 3.69          |
| RRc122      | $-1.16E-3 \pm 4.38E-5$ | $-166 \pm 32$ | 0.37         | 4.76          |
| RRc132      | $6.11E-4 \pm 2.85E-5$  | $-56 \pm 13$  | 0.26         | 3.72          |
| RRc132      | $6.08E-4 \pm 4.50E-5$  | $-42 \pm 16$  | 0.26         | 2.91          |
| RRc14       | $-1.64E-4 \pm 6.34E-5$ | $-212 \pm 31$ | 0.13         | 5.73          |
| RRc15       | $-1.27E-3 \pm 6.28E-5$ | $-183 \pm 31$ | 0.34         | 2.29          |
| RRc16       | $9.95E-5 \pm 5.82E-5$  | $-76 \pm 26$  | 0.37         | 3.07          |
| RRc17       | $1.20E-4 \pm 7.93E-5$  | $-79 \pm 38$  | 0.67         | 1.84          |
| RRc18       | $-8.16E-4 \pm 9.95E-5$ | $-150 \pm 31$ | 0.18         | 2.39          |
| RRc190      | $-3.35E-3 \pm 5.77E-5$ | $-75 \pm 23$  | 0.43         | 2.47          |
| RRc190      | $-1.36E-3 \pm 9.86E-5$ | $-90 \pm 37$  | 0.39         | 1.37          |
| RRc110      | $-1.73E-3 \pm 9.90E-5$ | $-211 \pm 20$ | 0.14         | 3.22          |
| RRd1        | $-1.26E-3 \pm 2.93E-5$ | $-149 \pm 15$ | 0.20         | 5.69          |
| RRd2        | $-1.16E-3 \pm 3.30E-5$ | $-89 \pm 12$  | 0.27         | 1.75          |
| RRd3        | $-1.71E-3 \pm 5.42E-5$ | $-222 \pm 20$ | 0.12         |               |

Notes.
1. $z_{e1,o}$ represents the redshift of the emission component of the “first apparition” in the observer’s frame.
2. $V_{e1,o}$ represents the radial velocity of the emission component of the “first apparition” in the stellar rest frame.
3. Flux$_{e1,o}$ indicates the normalized flux of the emission.
4. FWHM$_{e1,o}$ indicates the full width at half maximum of the emission.
5. The names like RRc11 mean that there is not only one spectrum of one star.
4. Discussion

Emission features in the spectra of RR Lyrae stars can be interpreted as shocks propagating through their pulsating envelopes. The brightest emission, the “first apparition,” can be produced by a shock forming below the photosphere near the time when the star achieves a minimum radius. The shock accelerates outward and the atoms deexcite after being excited by the shock in the radiative wake. The ramp pressure at the shock front provides energy that should be high enough to excite neutral hydrogen from the second quantum state upwards. The strength or values linked to the emission and the intensity of the shock front determine whether the emission is possible or not. Thus, our discovery possibly indicates the existence of shock waves in nonfundamental mode RR Lyrae stars.

The shock wake is suggested to be relatively narrow compared to the radius of the photosphere (Chadid 2011). Chadid et al. (2014) put forward a new scenario of shock propagation, which demonstrates that the $Sh_{PM1}$, $Sh_{PM2}$, and $Sh_{PM3}$ are receding in the Eulerian rest coordinates when advancing in the Lagrangian coordinates during the time interval of the ascending branch of the radial velocity curve.

We calculate the radial velocity of the emission component of the “first apparition” in the stellar rest frame, which is related to the physical conditions occurring in the radiative zone of the

| Table 3 |
|---------|
| Basic Properties of RRdI3 Derived from the Analysis of the ZTF Photometry |
| Object | $P_0$ (d) | $P_1$ (d) | $P_1/P_0$ | $A_0$ (mag) | $A_1$ (mag) |
| RRdI3 | 0.47701 | **0.35501** | 0.74424 | 0.125 | 0.237 |

*Note.* Period of the dominant mode is highlighted with bold font.

**Figure 5.** Prewhitening sequence for RRdI3. The uppermost panel shows the power spectrum of the original data. The lower panels display power spectra after removing consecutive frequencies. Feature lines are marked with different colors. Yellow lines are linear combinations expressed by $A_{0} f_{0} + A_{1} f_{1} + A_{2} f_{2}$, while $f_{j}$ is the daily cadence.
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Figure 6. Regeneration of the light curve of RRdl3 with the full light-curve solution. Blue points with error bars are observations from ZTF-g. Outliers are removed. Yellow points with error bars are regenerated points with the full light-curve solution with the same observing time as the observations. Panel (a): regenerated light curve. Panel (b): folded regenerated light curve using the first overtone period measured from observations.

Table 4

Full Light-curve Solution for RRdl3

| freq.id | $f$ (d$^{-1}$) | $A$ (mag) | $\sigma$ | $\phi$ (rad) | $\sigma$ | sig |
|---------|----------------|-----------|---------|-------------|---------|-----|
| $f_1-f_0$ | 0.72044 | 1.00300 | 0.037 | 0.002 | 1.089 | 0.064 | 30.314 |
| $f_1$ | 2.09641 | 2.81685 | 0.125 | 0.002 | 1.551 | 0.018 | 93.020 |
| $f_2$ | 4.19282 | 5.63370 | 0.074 | 0.002 | 3.847 | 0.010 | 147.464 |
| $f_3$ | 8.45055 | 7.37011 | 0.047 | 0.002 | 5.337 | 0.064 | 30.614 |
| $f_4$ | 8.73311 | 4.91326 | 0.037 | 0.002 | 1.428 | 0.135 | 13.998 |

Note. Consecutive columns are frequency id, frequency value, amplitude with standard error, and phase with standard error. The table is sorted by increasing frequency. According to the resolution calculated by data length, the last two digits of frequencies are given only for reference. In order to avoid overfitting, $f_1 - f_0$ and $2f_1$ are used instead of $f_2$ and $2f_1$ according to the process of prewhitening and fitting.

shock. The equation is as follows:

$$V_{c1,0} = c \frac{\lambda_{c1,0} - \lambda_{ab}}{\lambda_0},$$

where $\lambda_{c1,0}$ indicates the wavelength corresponding to the central wavelength of the emission component. $\lambda_{ab}$ represents the central wavelength of the absorption component. $\lambda_0$ is the laboratory wavelength.

The emission features in our sample spectra are rather moderate with respect to the continuum. Some of the measurement results of $V_{c1,0}$ exceed 100 km s$^{-1}$. At such a velocity, the emission of hydrogen would be far above the continuum if the exciting shock front were located in the photospheres. More studies on the propagation of radiation are needed at this point.

The possible detection of shock waves in the atmosphere of RR Lyrae also influences the understanding of the origin of the Blazhko effect. The Blazhko effect is a feature frequently observed on the light curves of RRab and RRc stars. According to Chadid et al. (2014), this effect is a complicated dynamical process due to the interactions of the multishock and the outflowing wind in stellar coronae. Blazhko RRab stars normally resemble RRc stars of the minimum Blazhko amplitude, but it cannot be confirmed that they share the same physical mechanism. The origins of the Blazhko effect in RRab and RRc stars were suspected to be totally different due to the absence of the detection of shock waves in RRc stars. Unfortunately, the small number of observed Blazhko RRc stars limits our knowledge of their embedded physics. The large variety of resonant, nonresonant, and chaotic possible states should be taken into consideration when explaining low-amplitude variations (Molnár et al. 2012a, 2012b). In this sense, our research will serve as a valuable constraint on the future investigation of long-term modulations in nonfundamental mode stars and provide a clue to the complicated shock mechanism.

5. Analysis of Frequency Components in RRdl3

According to the photometric observations from ZTF DR2, we notice that the light curve of one of the multimode RR Lyrae stars with the “first apparition,” RRdl3, may feature Blazhko-type modulation. Blazhko-type modulation in four double-mode RR Lyrae stars has been discovered in the globular cluster M3 by Jurcsik et al. (2014). Smolec et al. (2015) also reported the discovery of 15 RRd stars in the Optical Gravitational Lensing Experiment Galactic bulge collection.

We analyze the g-band light curve of RRdl3 with a timespan of 394.07 days, using a standard successive prewhitening technique (Moskalik & Kołaczkowski 2009). Outliers have been removed. At each step we fit the data using a nonlinear least-squares procedure with the sine series of the following form:

$$m(t) = m_0 + \sum_{k=1}^{N} A_k \sin(2\pi f_k t + \phi_k),$$

where $f_k$ are independent frequencies detected in the discrete Fourier transform of the data and their possible linear combinations. The residuals of the fit are used to search for frequencies in the next step. Then, a new Fourier series consisting of all frequencies detected so far is fitted to the data again. The process continues until no new significant frequency is detected and the residuals are virtually white noise. The frequencies, e.g., $f_a$ and $f_b$, are regarded as unresolved if...
$|f_0 - f_i| < 2/T$, where $T$ represents the length of the observed data set. Here, $2/T \approx 0.005$.

The prewhitening sequence for RRd3 is displayed in Figure 5. Apart from $f_0, f_1$, and their linear combinations $\lambda_0 f_0 + \lambda_1 f_1$, we detect many significant signals of frequencies that can be expressed as $\lambda_0 f_0 + \lambda_1 f_1 + \lambda_c f_c$, where $f_c \approx 1.003$. They manifest in the spectrum of frequency as equally spaced multiplets around main frequencies and their harmonics. Obviously, $f_c$ is generated from the daily cadence, which is a major problem for data analyses in ground-based time-domain surveys (see Section 5.3 in Chen et al. 2020). In the prewhitening process, after we removed the main peak $\lambda_0 f_0 + \lambda_1 f_1$, the side peaks $\lambda_0 f_0 + \lambda_1 f_1 + \lambda_c f_c$ disappear as well.

We find a full light curve solution for RRd3. Basic properties of RRd3 derived from the analysis of ZTF-g are displayed in Table 3. The period of the dominant mode is highlighted in bold font. According to the resolution calculated by the data length, the last two digits of periods are given only for reference. The full light-curve solution is shown in Table 4. In order to avoid overfitting, $f_1 - f_0 + f_c$ and $2f_1 + f_0 + f_c$ are used instead of $f_1 - f_0$ and $2f_1 + f_0$ according to the process of prewhitening and fitting. The regenerated light curves are displayed in Figure 6.

The RR Lyrae stars that show additional close side peaks at the fundamental and/or first overtone frequency are suspected of long-term modulation (Smolec et al. 2015). The signals of modulation are shown as equally spaced triplets or close doublets in a typical ground-based observation (Alcock et al. 2003; Moskalik & Poretti 2003). The inverse of separation on the frequency spectrum between multiplet components is the modulation period. In Figure 7, we display the amplifying pattern. We can see a series of weak signatures, which indicates a possible Blazhko-type modulation, with $f_B \approx 0.022$ and $P_B \approx 44.483$d. Visible signals are seen at $f_0 - f_B, f_0 + f_B, f_1 - f_B$, and $f_1 + f_B$. But the signals are not significant enough compared to the others, probably because they are hampered by a lack of quantitative data. A larger and more homogenous photometric data set is required for a clearer Blazhko-type modulation analysis.

6. Conclusions

We report the first systematic search for Balmer emission features in first-overtone and multimode RR Lyrae stars, taking advantage of large spectral surveys. In this work, we discover 23 cases in total, including 10 RRc stars in SDSS, 10 RRc in LAMOST, and 3 RRd stars in LAMOST. The basic parameters and measurements of the properties of the “first apparitions” are displayed in Tables 1 and 2.

The targets are selected through our handcrafted one-dimensional pattern recognition pipeline, using low-resolution single-epoch spectra. We fit the “first apparition” using two Sérsic profiles, and estimate uncertainties by error propagation for the covariance matrix and Monte Carlo method. We calculate the radial velocities of the emission lines, which are related to the physical conditions occurring in the radiative zone of the shock in which the hydrogen emission is formed. Moreover, with photometric observations from ZTF DR2, we present a detailed analysis of the light curve of RRd3. We find a full light-curve solution for RRd3. The result suggests that a series of weak signatures possibly indicates the period of its Blazhko-type modulation. To draw a solid conclusion on this point, a larger and more homogenous photometric data set is still required for a more precise analysis.

The detection of hydrogen emission lines in the first-overtone and multimode RR Lyrae variables indicates the possible existence of shock waves, which gives us a new insight into the origin of the Blazhko effect. With further
observational evidence of shock wave signals in nonfundamental mode RR Lyrae stars, we will finally unveil the role of shock waves in the long-term modulation of them.

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