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Authors: The user has provided a list of names: "Yue Huang, Min Fang, Gaochao Liu, Xianzhong Zheng, Sarah Ann Bird, Yang Huang, Jianrong Shi, Jiangtao Wang, Huawei Zhang, Haijun Tian et al"

This appears to be an author list for a scientific paper. The user wants me to translate this from Simplified Chinese to English. However, this is already in English (names are either English or Pinyin transliterations). The only Chinese element is "et al"which is actually Latin, but commonly used in Chinese academic writing as well.

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The text is: "Yue Huang, Min Fang, Gaochao Liu, Xianzhong Zheng, Sarah Ann Bird, Yang Huang, Jianrong Shi, Jiangtao Wang, Huawei Zhang, Haijun Tian et al"

This is already in a format suitable for English academic papers. The names are: - Yue Huang (黄悦) - Chinese name in Pinyin - Min Fang (方敏) - Chinese name in Pinyin - Gaochao Liu (刘高超) - Chinese name in Pinyin - Xianzhong Zheng (郑先忠) - Chinese name in Pinyin - Sarah Ann Bird - English name - Yang Huang (黄洋) - Chinese name in Pinyin - Jianrong Shi (施建荣) - Chinese name in Pinyin - Jiangtao Wang (王江涛) - Chinese name in Pinyin - Huawei

Zhang (张华伟) - Chinese name in Pinyin - Haijun Tian (田海军) - Chinese name in Pinyin - et al - Latin abbreviation for "and others"

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Abstract

The user wants me to translate a Chinese academic text to English. Let me analyze the requirements:

1. **CRITICAL REQUIREMENTS**:
   - Preserve ALL LaTeX commands and placeholders exactly
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   - 深度学习 => deep learning

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Preamble

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Probing the Galactic Halo with RR Lyrae Stars. VI. The Radial Velocity Curve Templates of RRc Stars

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Abstract

We present radial velocity (RV) curve templates of RR Lyrae first-overtone (RRc) stars constructed with the Mg I b triplet and Hα lines using time-domain Medium-Resolution Survey spectra of seven RRc stars from Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) Data Release 9. Additionally, we derive the relation between the stellar RV curve amplitudes and g-band light curve amplitudes from Zwicky Transient Facility (ZTF) public survey. For those RRc stars without ZTF g-band light curves, we provide the conversions from the light curve amplitudes in ZTF r- and i-bands, Gaia G-band, and V-band from the All-Sky Automated Survey for Supernovae to those in ZTF g-band. We validate our RV curve templates using the RRc star SV Scl and find the uncertainties of systemic RV are less than 2.11 km s^{-1} and 6.08 km s^{-1} based on the Mg I b triplet and Hα lines, respectively. We calculate the systemic RVs of 30 RRc stars using the RV curve templates constructed with the Mg I b triplet and Hα lines and find the systemic RVs are comparable with each other. This RV curve template will be particularly useful for obtaining the systemic RV of RRc using the LAMOST spectroscopy.

Key words: stars: variables: RR Lyrae –Stars –techniques: radial velocities

1. Introduction

RR Lyrae stars are old, metal-poor pulsating variables. After undergoing an extended period of evolution on the main sequence, they eventually reach the horizontal branch stage of core-helium-burning and enter the instability strip (Smith 1995). RR Lyrae stars are commonly referred to as classical radially pulsating stars. According to the pulsation pattern, they can be divided into three types: fundamental mode (RRab), first-overtone mode (RRc), or double-mode (RRd) (Alcock et al. 2000). The well-established period–luminosity relation of RR Lyrae stars warrants them as reliable standard candles for both galactic and extragalactic distance determination (Deng et al. 2012; Savino et al. 2022). Their distinct characteristics also make them valuable for research on the structure and evolution of the Galaxy (Fabrizio et al. 2019; Fiorentino et al. 2022).

To explain the properties and origin of the substructure traced by RR Lyrae stars, accurate kinematic data are crucial. As RR Lyrae stars are a class of pulsating variable stars, their radial velocity (RV) amplitude due to pulsation can reach 80–130 km s^{-1} for RRab and 20–60 km s^{-1} for RRc based on the Hα line (Braga et al. 2021). Therefore, to measure the systemic velocities of RR Lyrae stars, it is necessary to correct for the pulsation velocity.

Oke (1966) first proposed to construct the RV curve template using an RRab star, X Ari, based on metal lines and the Hγ line. Since then, significant efforts have been made to establish RV curve templates for RRab stars (Liu 1991; Sesar 2012). Recently, RV curve templates of RRc stars have been developed (Sneden et al. 2017; Braga et al. 2021). Compared with those of RRab stars, the RV curve templates of RRc stars have been studied much less due to their smaller amplitudes that are easily confused with W UMa stars in frequency analysis, and most RRc stars are too faint for high-resolution spectral observations (Govea et al. 2014). The Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) Medium-Resolution Survey (MRS, Liu et al. 2020a; Zong et al. 2020) started observations in October 2018, encompassing a time-domain survey aimed at investigating variable targets over repeated observations. This dedicated extension of the survey facilitates the construction of the RV curve templates of RRc stars.

This work is one of a series of studies of the galactic halo with RR Lyrae stars. In Paper I of this series, Liu et al. (2020b) constructed a catalog of RR Lyrae stars with position, systemic RV and metallicity information. However, when calculating the systemic RV of RRc stars, they cannot find a suitable RV curve template for RRc. Based on this catalog, Wang et al. (2022, Paper II) studied the global structure and substructures of the galactic stellar halo and Liu et al. (2022, Paper III) analyzed the chemical and kinematical properties of the halo. In Paper IV, Zhang et al. (2023) investigated the origin of the Oosterhoff dichotomy of RR Lyrae stars. In addition, Li et al. (2023) trained relations between spectroscopic [Fe/H] (Liu et al. 2020b) and Fourier parameters from the RR Lyrae light curves provided by Gaia Data Release 3 (DR3) (Clementini et al. 2023), and then presented a large sample of over 130,000 RR Lyrae stars with precise metallicity and distance measurements. Using this sample, Cabrera Garcia et al. (2024, Paper V) identified 97 Dynamically Tagged Groups of RR Lyrae stars and explored their associations with recognized substructures of the Milky Way. In this work, we construct RV curve templates for RRc stars using the data from the LAMOST MRS project.

We organize the paper as follows. In Section 2, we introduce the RRc sample and describe their photometry and spectroscopy. In Section 3, we analyze the light curves and present the RV curves of our targets. In Section 4, we construct the RV curve templates for RRc stars. In Section 5, we provide the relation between RV curve amplitudes and Zwicky Transient Facility (ZTF) g-band light curve amplitudes. We describe the systemic RV of RRc stars and supply the systemic RVs for 30 RRc stars by using the RV curve templates in Section 6. Finally, we summarize our results in Section 7.

2. Data

2.1. RR Lyrae Sample

The Gaia space telescope was launched on 2013 December 19 from the Guiana Space Center (van Leeuwen et al. 2017). The astrometric instrument of the Gaia satellite collects the G-band (330–1050 nm) photometry. The limiting magnitude is 20.7 mag and saturation occurs at 6 mag in G-band. Gaia is also equipped with photometer spectra and the Radial Velocity Spectrometer, enabling it to obtain both photometric and spectroscopic information.

Gaia DR3 provides the largest all-sky catalog of RR Lyrae stars (Clementini et al. 2023). This catalog encompasses an aggregate count of 270,905 RR Lyrae stars, including 174,947 RRab stars, 93,952 RRc stars, and 2006 RRd stars. These RR Lyrae stars have been confirmed using the Specific Object Study Cep & RRL pipeline, which was specially developed for analyzing the light curves of variable stars in Gaia DR3; this pipeline returns additional parameters such as

Fourier parameters, amplitude and phase (Gaia Collaboration et al. 2023). Our initial sample consists of RRc stars from this catalog.

2.2. Spectroscopic Data

The LAMOST MRS Data Release 9 (DR9) (R 7500) has totally released 23,510,805 single exposure spectra and 6,409,783 coadded spectra. In a single exposure, LAMOST can obtain a blue (B) band (4950 to 5350 Å) and a red (R) band (6300 to 6800 Å) spectrum. The coadded spectra of the B and R bands are obtained by combining multiple single-exposure spectra, which obscures the RV variations of RR Lyrae stars. Therefore, we exclusively use single exposure spectra.

We cross-match our initial sample with the data set of spectra from LAMOST MRS DR9, resulting in 4312 single exposure spectra for 201 RRc stars. We select spectra with signal-to-noise ratio (S/N) > 5. We identify seven stars with more than 10 useful spectra and use them to construct the RV curve templates.

2.3. Light Curve Extraction

To obtain the light curves of our sample, we use three data sets: Zwicky Transient Facility Public Data Release 15 (ZTF DR15; Bellm et al. 2019), Gaia DR3, and All-Sky Automated Survey for Supernovae (ASAS-SN; Hart et al. 2023). ZTF DR15 provides gri-band photometric data, Gaia supplies G-band photometric data, and ASAS-SN offers V-band photometric data.

ZTF is a large optical sky survey employing customized gri filters, enabling a comprehensive investigation of the celestial hemisphere in the northern hemisphere. The survey design prioritizes efficiency over traditional photographic surveys by utilizing a new CCD camera that for the first time fills the focal plane of the wide-field Palomar 48 inch Schmidt telescope. The respective limiting magnitudes for the g-band, r-band, and i-band are 20.8, 20.6, and 19.9 mag. Observation time for ZTF is allocated to public, private, and collaborative survey initiatives. The ZTF DR15 includes data from both public surveys and private surveys, with cut-off dates of 2022 November 9 and 2021 July 9 respectively.

ASAS-SN uses four 2k$×$2k CCD cameras with 14 cm telescopes located in the northern and southern hemispheres to perform the all-sky imaging survey. The survey employs two bands, with the limiting magnitudes in the V-band and g-band being 17.5 and 18.5 mag, respectively. The ASAS-SN online database Sky Patrol 2.0 (Hart et al. 2023) provides continuously updated light curves for approximately 111 million celestial targets derived from numerous external catalogs of stars, galaxies, and solar system objects.

We extract the RRc light curves by using the Gaia DR3 provided RA and DEC to search for matches within ZTF DR15, Gaia DR3 and ASAS-SN using a one arcsecond radius. The number of data points per light curve (in ZTF g-, r-, and i-bands, Gaia G-band, and ASAS-SN V-band) is presented in Table 1. The number of data points in the i-band light curves is much smaller than those in g- and r-bands since the observing strategy of ZTF focused on the g- and r-bands in the early stages of the survey and the ZTF public surveys were only in the gr-bands (Ngeow et al. 2022). By cross-matching our initial spectral sample consisting of the whole Gaia DR3 RRc catalog with ZTF DR15, Gaia DR3 and ASAS-SN photometry, we obtain light curves in each band and construct the relations between the light curve amplitudes in ZTF g-band with the light curve amplitudes in ZTF r- and i-band, Gaia G-band and ASAS-SN V-band (Appendix A).

3. Analysis

3.1. Phase and Amplitude of Light Curves

The Fast Lomb–Scargle Periodogram (Press & Rybicki 1989) is a widely recognized approach for detecting periodicity in irregularly sampled time-series data. In this work, we use the implementation of this approach from the astroML/gatspy[10] package (VanderPlas & Ivezić 2015) to analyze the frequencies of the light curves of our targets. After obtaining the frequency of individual light curves, we fit them using the following Fourier function:

$$m(t) = A_0 + \sum_{i=1}^{N} A_i \sin(2\pi i f_0 t + \phi_i)$$

where f_0 is the frequency calculated with gatspy. We interpolate the resulting best-fit light curves for each band individually. We take the moment when the source is brightest in that band as the phase zero and fold the light curves. As an example, we show the folded g-band light curves of our targets in Figure 1. We fold the light curves in different bands using the same approach. In Table 2 we list the periods and the epochs corresponding to phase zero ($T_{\max}$) derived from the light curves in ZTF g-band, Gaia G-band, and ASAS-SN V-band. We calculate the offset of the period and phase zero of the Gaia G-band and ASAS-SN V-band with respect to the ZTF g-band. The differences of period have a negligible impact as demonstrated (Δperiod $< 10^{-4}$ days) and the differences of phase are all within 0.1.

We also measure the peak-to-peak amplitudes (Amp) of the light curves in different bands and include these in Table 2. Because of the high-cadence time-series photometry of the g-band, we use the parameters of the g-band to construct our RV curve templates.

3.2. Estimation of Radial Velocity

Stellar RV curves have different shapes depending on the different spectral lines used to perform the measurement. These unique spectral lines are in different atmospheric layers of the star and depend on properties such as temperature. For example, the metal lines are close to the photosphere but the Hα line is generated higher in the atmosphere (Sneden et al. 2017). For individual Balmer lines, their RV curve amplitudes (Amp(RV)) are different (Sesar 2012). But for the metal lines, such as Fe, Mg I b triplet, and Na doublet, their Amp(RV) values agree with each other within the uncertainties (Braga et al. 2021). In this work, we perform RV measurements individually using the Hα line and Mg I b triplet (Mg b1, b2, b3). Figure 2 displays the regions of one of spectra in our sample.

We first cross-match our sample with the catalog of the LAMOST DR9 RV zero-points (Zhang et al. 2021), which is continuously updated on GitHub. Using these zero-points, we correct the RVs of our spectra. We rely on the cross-correlation function (CCF) module in laspec.ccf to estimate RVs of our targets (Zhang et al. 2021). For each target, we select the spectrum with the highest S/N as the initial template. We use this initial template and cross-correlate it with the other spectra of the sample target. The peak of the CCF is taken as the RV value. We shift each spectrum by its RV and co-add all the shifted spectra for the target into one spectrum, which is taken as the final template. We use the templates to re-estimate the RVs and show them in Table B1.

To estimate the RV uncertainty induced by the noise on the spectra, we first subtract the template from the RV-corrected individual spectra. From the residual spectrum, we calculate the standard deviation which is a combination of noise on the template and the target spectrum. Using the derived standard deviation and assuming a normal distribution of noise, we add the noise to the template. We then estimate the RV from the noised template in the same way as we did for the target spectra. We repeat this process 1000 times. The standard deviation of the 1000 RVs is taken as the measured RV uncertainty of the target spectrum. The total RV uncertainty, listed in Table B1, also includes the mean uncertainties of the RV zero-points and 1 km s^{-1} uncertainty that is due to systematics from Zhang et al. (2021).

In Figure 3, we present the variation of RV with phase for each star, which is folded based on the period and $T_{\max}$ estimated by ZTF g-band. Some RV measurements (marked with black boxes in Figure 3) deviate from the expected values of the RV curve by more than 5σ and are excluded from the following construction of the RV curve templates.

4. Construction of Velocity Templates

We construct two RV curve templates of RRc stars using the seven targets in LAMOST MRS. We obtain the two templates by using the RVs derived from the Mg I b triplet and Hα lines separately.

We adopt the following Fourier function to fit the RV curves for each star:

$$\mathrm{RV}_j(\phi) = B_j + C_j \sum_{i=1}^{N} [a_i \sin(2\pi i\phi) + b_i \cos(2\pi i\phi)]$$

where B and C change from source to source, j corresponds to each source within the sample, a and b are the same for all sources, and i corresponds to the order of the Fourier function.

We use EMCEE (Foreman-Mackey et al. 2013) to perform a Markov Chain Monte Carlo (MCMC) fitting on the RV curves of each star. The likelihood function is as follows:

$$\ln \mathcal{L} = -\frac{1}{2} \sum_{n} \left[\frac{(\mathrm{RV}_{\mathrm{obs}} - \mathrm{RV}_{\mathrm{model}})^2}{\sigma_{\mathrm{RV}}^2} + \ln(2\pi\sigma_{\mathrm{RV}}^2) \right]$$

where n represents the count of observed data points, $\mathrm{RV}_{\mathrm{obs}}$ is the observed RV value, $\mathrm{RV}_{\mathrm{model}}$ is the model' s prediction for the observed value, and σ_{RV} is the RV uncertainty.

We combine RVs from all stars to construct the RV curve templates. Since these stars have different RV amplitudes, we normalize the RVs for each star using:

$$\mathrm{RV}_{\mathrm{normal}} = \frac{\mathrm{RV} - \mathrm{RV}_{\mathrm{min}}}{\mathrm{RV}_{\mathrm{max}} - \mathrm{RV}_{\mathrm{min}}}$$

where $\mathrm{RV}_{\mathrm{max}}$ and $\mathrm{RV}_{\mathrm{min}}$ refer to the maximum and minimum values of the fitted RV curve. The normalized RVs of our targets are displayed in Figure 4.

The average shape of the normalized RV curve is defined using a Fourier function. The best-fit results are shown in Figure 4 and their Fourier parameters are listed in Table 3. To estimate the uncertainty, we calculate the rms scatter around the template and label it in Figure 4. We compare our RV curve templates for Mg lines and Hα line with the RV curve templates provided by Sneden et al. (2017, hereafter S17) and Braga et al. (2021, hereafter B21) in Figure 4. The shape of the RV template in our work based on Mg lines is similar to the one in B21. For an RRc star with an Amp(g) of 0.5 mag, the largest deviation between the two templates is about 1.55 km s^{-1}. The RV template constructed using Hα in this work is similar to the one from Mg lines but different from those from S17 and B21. For an RRc star with an Amp(g) of 0.5 mag, the largest difference between our template and the one from S17 is 5.9 km s^{-1} at Phase 0.7. As shown in the right panel of Figure 4, the data from the LAMOST MRS also exhibit large dispersion in the phase range where the templates from this work and those from S17 and B21 disagree. This indicates that the shape of the Hα RV curves may vary from source to source. More data from the LAMOST MRS are required to address this issue.

5. Amplitude Correlations

The amplitude correlations of RR Lyrae stars were first noted by Liu (1991). Using 22 RRab stars, they discovered that the amplitude of the light curves can be converted into the amplitude of Amp(RV). To ensure internal consistency within our analysis, we offer conversion equations from Amp(g) to Amp(RV) derived from measurements of Mg I b triplet and Hα lines, respectively.

Figure 5 shows the trend of Amp(RV) and Amp(g). Among our seven RRc stars with LAMOST MRS spectra, we find one with Amp(g) = 0.37 which deviates from the majority of the data and we are unable to confirm its accuracy. Hence, we limit our results to the range of Amp(g) greater than 0.47 and less than 0.68. We use a linear least-squares fit to Amp(RV) as a function of Amp(g) and find:

$$\mathrm{Amp(RV)}_{\mathrm{Mg}} = (30.76 \pm 2.00) \times \mathrm{Amp(g)} - (10.34 \pm 1.21)$$

$$\mathrm{Amp(RV)}_{\mathrm{H}\alpha} = (81.75 \pm 6.41) \times \mathrm{Amp(g)} - (3.67 \pm 3.67)$$

6. Systemic Velocity and its Uncertainty

The RV of RR Lyrae stars comprises the systemic RV (RV_γ) and the stellar pulsation velocity. There are ongoing debates regarding the derivation of RV_γ from observed RV curves. Sesar (2012) takes the RVs at the phase of 0.5 as the RV_γ. Oke et al. (1962) find the RV_γ of RRab star SU Dra is consistent with the observed RV at phase 0.4. S17 use the average value of the RV curve over one pulsation period as RV_γ. Given that spectral lines represent the velocity of a particular mass layer in the stellar atmosphere, different lines correspond to different phases and an error of 1 km s^{-1} in the systemic RV leads to a change of the order of 10% in the evaluation of the maximum stellar radius (Bono et al. 1994). To mitigate potential bias, we assume RV_γ to be equal to the average value of our derived RV curve.

The template constructed in this work can be used to calculate the systemic RV for the RRc with only one RV measurement. First, we use Amp(RV) to rescale the normalized RV template. Then, we match the enlarged RV template to the RV at the corresponding phase. The average value of our derived RV curve over one pulsation period is taken as the RV_γ of the source.

To verify our RV templates, we use a well-observed RRc from B21, SV Scl, which has been observed a total of 54 times using the du Pont telescope. Since SV Scl is independent from our sample, it serves as an ideal validation source for our RV curve templates. We adopt the RV_γ (hereafter $\mathrm{RV}_\gamma^{\mathrm{B21}}$) of SV Scl from B21 (see their Tables 8 and 9). We apply our RV curve templates to fit the RV curves of each observation of SV Scl and estimate the systemic RVs for each fitting RV curve. We use error propagation to determine the uncertainty on RV_γ and derive the offsets $\Delta\mathrm{RV}_\gamma = \mathrm{RV}_\gamma^{\mathrm{Temp}} - \mathrm{RV}_\gamma^{\mathrm{B21}}$ for each observation to estimate the accuracy for our two RV curve templates. Figure 6 displays the fitting RV curve for each point and the residual of ΔRV_{γ}. For the Mg lines (Hα line), the median ΔRV_{γ} is always less than 1.15 km s^{-1} (3.14 km s^{-1}) and the standard deviation of ΔRV_{γ} is always less than 2.11 km s^{-1} (6.08 km s^{-1}). We note that the median and standard deviation of ΔRV_{γ} for the Mg lines are always smaller than those of the Hα line. The estimated RV_{γ}s of the Hα line are overestimated in phases 0.9 and 1.0 due to a rapid change in RRc RVs during these phases that exhibited increasing blurring of the spectrum (Sesar 2012). In all cases, we also average the inferred RV_{γ}s of each RV observation and find that the ΔRV_{γ}s are all smaller than 1.0 km s^{-1}.

We now use our two derived RRc RV curve templates to estimate the systemic velocities for stars from our original Gaia DR3-LAMOST MRS DR9 cross-matched sample. We select 30 RRc stars as our sample, each with at least one single exposure spectrum and S/N exceeding 10. In addition, we also calculate their periods, amplitudes, and $T^{g}_{\max}$. We use our RV curve templates to fit each source and estimate RV_{γ} for each star. In the case of multiple observations of an RRc star, we use the average RV_{γ} as their systemic RV, which are presented in Table 4. Our final estimated RV_{γ} values for each star using both the Mg lines and Hα line are highly consistent, generally consistent, and the standard deviation offset is less than 4.0 km s^{-1}.

7. Summary

In this paper, we present RV curve templates for RRc stars based on the well-identified Mg I b triplet and Hα lines. First, we selected seven RRc stars from LAMOST MRS DR9, each with more than 10 useful spectra exceeding an S/N of 5. We correct the RV zero-points of these spectra and then calculate their relative RVs. Furthermore, we acquire the light curves of our sample from ZTF DR15 (gri-band), Gaia DR3 (G-band) and ASAS-SN (V-band). We determine the periods and amplitudes and assume that the phase zero of the RV curves corresponds to the time of maximum light in the photometry. As a result, we construct two RV curve templates using our sample and use a Fourier function to define the analytical form of the templates. To validate our RV curve templates, we select the RRc star SV Scl, which is independent from our sample, to perform the tests. We apply our two RV curve templates to each RV measurement of SV Scl and find that the medians of ΔRV are smaller than the standard deviations. We also find that the median and standard deviation of ΔRV for the Mg lines are always smaller than those of the Hα line and that the estimated values for RV_{γ} of the Hα line are overestimated in phases 0.9 and 1.0.

We explore the relations between Amp(g) and Amp(RV) for our RV curve templates. The conversion relationships apply only to a range of Amp(g) from 0.47 to 0.68. The correlations derived in this paper can better apply the RV curve templates and scale the RV curve more correctly. To further enhance the versatility of our templates across different bands, we also derive the correlations between the light curve amplitudes of ZTF g-band with the light curve amplitudes of ZTF i- and r-bands, Gaia G-band and ASAS-SN V-band for RRc stars. However, it is important to acknowledge a limitation in our sample, namely the exclusive coverage of Mg I b triplet and Hα, with no inclusion of other Balmer lines or metallic lines. This restriction may affect the broader applicability of our templates to other frequency bands.

Acknowledgments

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Appendix A: Relationship between the Amplitudes of Light Curves in Different Bands

Throughout this study, whether deriving the conversion between RV amplitudes and light curve amplitudes or establishing our RV templates, we predominantly rely on data from the ZTF g-band. In order to extend the applicability of our results, we also cross-match the whole Gaia DR3 RRc catalog with ZTF DR15, Gaia DR3 and ASAS-SN to obtain 24,935 light curves in ZTF g-band, 3123 light curves in ZTF i-band, 28,051 light curves in ZTF r-band, 40,472 light curves in Gaia G-band, and 11,378 light curves in ASAS-SN V-band.

Figure A1 presents the relationships between the light curve amplitudes of ZTF g-band with the light curve amplitudes of ZTF i- and r-bands, Gaia G-band and ASAS-SN V-band for RRc stars. The additional amplitudes in different bands are closely related with Amp(g) excluding Amp(V). The Amp(V) has a large scatter. To verify outliers, we also calculate the median of the light curves in the ZTF g-band and ASAS-SN g- and V-bands, as illustrated in Figure A2.

We classify the abnormal values as those $>3\sigma$ and mark them with red dots in Figure A2. By checking the ZTF images of these stars, we identify two primary reasons for this phenomenon: these stars are either clustered in densely populated regions or have brighter stars in close proximity. Therefore, the points marked in red in Figure A2, the same as red points in Figure A1, were removed when fitting the relationship between ASAS-SN Amp(V) and ZTF Amp(g). The transformation equations provided by these relationships are:

$$\mathrm{Amp(r)} = (0.70 \pm 0.031) \times \mathrm{Amp(g)} + (0.038 \pm 0.031)\ \mathrm{mag}$$

$$\mathrm{Amp(i)} = (0.55 \pm 0.031) \times \mathrm{Amp(g)} + (0.051 \pm 0.031)\ \mathrm{mag}$$

$$\mathrm{Amp(G)} = (0.76 \pm 0.031) \times \mathrm{Amp(g)} + (0.031 \pm 0.031)\ \mathrm{mag}$$

$$\mathrm{Amp(V)} = (0.70 \pm 0.031) \times \mathrm{Amp(g)} + (0.038 \pm 0.031)\ \mathrm{mag}$$

Appendix B: Radial Velocity Measurements

In Table B1, we present all the RV measurements. The descriptions of the columns are described in the main text.

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Note: Figure translations are in progress. See original paper for figures.