Near-infrared Census of RR Lyrae Variables in the Messier 3 Globular Cluster and the Period–Luminosity Relations

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Abstract

We present new near-infrared (NIR), JHKs, time-series observations of RR Lyrae variables in the Messier 3 (NGC 5272) globular cluster using the WIRCam instrument at the 3.6 m Canada–France–Hawaii Telescope. Our observations cover a sky area of $\sim 21' \times 21'$ around the cluster center and provide an average of 20 epochs of homogeneous JHKs-band photometry. New homogeneous photometry is used to estimate robust mean magnitudes for 175 fundamental-mode (RRab), 47 overtone-mode (RRc), and 11 mixed-mode (RRd) variables. Our sample of 233 RR Lyrae variables is the largest thus far obtained in a single cluster with time-resolved, multiband NIR photometry. NIR-to-optical amplitude ratios for RR Lyrae in Messier 3 exhibit a systematic increase moving from RRc to short-period ($P < 0.6$ day) and long-period ($P \geq 0.6$ day) RRab variables. We derive JHKs-band period–luminosity relations for RRab, RRc, and the combined sample of variables. Absolute calibrations based on the theoretically predicted period–luminosity–metallicity relations for RR Lyrae stars yield a distance modulus, $\mu = 15.041 \pm 0.017$ (statistical) $\pm 0.036$ (systematic) mag, to Messier 3. When anchored to trigonometric parallaxes for nearby RR Lyrae stars from the Hubble Space Telescope and the Gaia mission, our distance estimates are consistent with those resulting from the theoretical calibrations, albeit with relatively larger systematic uncertainties.

Unified Astronomy Thesaurus concepts: RR Lyrae variable stars (1410); Stellar pulsations (1625); Globular star clusters (656); Distance indicators (394); Distance measure (395)

Supporting material: machine-readable tables

1. Introduction

RR Lyrae variables are low-mass ($0.5 \lesssim M/M_\odot \lesssim 0.8$), old (>10 Gyr) stars that are located in a region between the cross section of the horizontal branch and the classical “instability strip” in the Hertzsprung–Russell diagram. These horizontal branch stars pulsate during their central helium burning evolutionary phase, similar to intermediate-mass ($3 \lesssim M/M_\odot \lesssim 10$) classical Cepheids. RR Lyrae follow a visual (V-band) magnitude–metallicity relation with negligible dependence on pulsation periods unlike classical Cepheids (Bono et al. 2003). The reason for this different behavior is that the bolometric correction’s sensitivity to effective temperature becomes significant only at longer wavelengths (R band onwards; Catelan et al. 2004). Indeed, RR Lyrae exhibit well-defined period–luminosity relations (PLRs) at infrared wavelengths, first demonstrated in pioneering work by Longmore et al. (1986), which makes them excellent distance indicators (see recent reviews, Beaton et al. 2018; Bhardwaj 2020). RR Lyrae play a key role in our understanding of stellar evolution and pulsation (Catelan 2009), and as stellar population tracers for Galactic archeology and the cosmic distance scale (Beaton et al. 2018; Kunder et al. 2018).

Globular clusters (GCs) typically host a rich and homogeneous population of RR Lyrae stars. Messier 3 (M3 or NGC 5272), located at a distance of $\sim 10$ kpc, hosts one of the largest samples of RR Lyrae with a dominant population of fundamental-mode RR Lyrae (RRab) variables (Clement et al. 2001). M3 has a mean metallicity of [Fe/H] $\sim -1.5$ dex (Harris 2010), and the observed period distribution of its RR Lyrae population exhibits a sharp peak at a fundamental pulsator period of 0.55 day (Jurcsik et al. 2017), indicating that it is a typical Oosterhoff I type (OoI; Oosterhoff 1939; Fabrizio et al. 2019) cluster. While multiple stellar populations have been detected along the red giant branch of M3 (e.g., Massari et al. 2016; Lee & Sneden 2020), no significant variation has been detected in the iron abundance (Sneden et al. 2004). Furthermore, helium enhancement ($\Delta Y \lesssim 0.02$) has been suggested to explain observed properties of horizontal branch stars (Dalessandro et al. 2013; Valcarce et al. 2016; Denissenkov et al. 2017).

Insignificant interstellar reddening (VandenBerg et al. 2016) and the close proximity of M3 motivated several detailed long-term photometric investigations at optical wavelengths (Bakos et al. 2000; Cacciari et al. 2005; Benko 2006; Jurcsik et al. 2012, 2017, and references therein). Optical photometry has been used to investigate the Blazhko effect, multimode pulsations, and period doubling in M3 RR Lyrae variables.
(Jurcsik et al. 2015; Jurcsik 2019). The RR Lyrae population in the M3 cluster has also been explored at ultraviolet wavelengths (Siegel et al. 2015). At near-infrared (NIR) wavelengths, Longmore et al. (1990) derived $K_s$-band PLRs for RR Lyrae in GCs including 49 variables in the outer region of M3. Apart from that, NIR photometry of RR Lyrae in M3 has been limited to a sample of seven RR Lyrae in the inner region of the cluster (Butler 2003).

M3 has been the subject of several theoretical studies aimed at reproducing the observed pulsation properties and, in particular, the period distribution of its RR Lyrae population (Catelan 2004; Castellani et al. 2005; Fadeyev 2019). Castellan (2004) showed that the predicted period distribution based on canonical horizontal branch models is inconsistent with observations, while Castellani et al. (2005) suggested that a bimodal mass distribution would be required to reproduce the period distribution with canonical models. Marconi & Degl’Ippocenti (2007) accurately modeled optical light curves of M3 RR Lyrae using nonlinear pulsation models with [Fe/H] $\sim$ −1.34 dex (Carretta & Gratton 1997), and estimated a distance modulus of 15.10 ± 0.10 mag. Using horizontal branch models, Denissenkov et al. (2004) found good agreement with observed properties of RR Lyrae and non-variable horizontal branch stars for a distance modulus and reddening of $\mu = 15.02$ mag and $E(B-V) = 0.013$ mag, respectively.

RR Lyrae as distance indicators have gained significance with increasing NIR observations especially in GCs (Sollima et al. 2006; Coppola et al. 2011; Stetson et al. 2014; Braga et al. 2015, 2018; Navarrete et al. 2015). These horizontal branch variables can complement the tip of the red giant branch stars to complement the Population II variables can complement the tip of the red giant branch stars to derive the PLRs and estimate the dependence on metal abundance (Sollima et al. 2006). While theoretical models predict a significant metallicity coefficient of the RR Lyrae period–luminosity–metallicity (PLZ) relation (e.g., Catelan et al. 2004; Marconi et al. 2015), it is still a topic of active debate considering the paucity of RR Lyrae with both high-resolution spectroscopic metalicities and precise parallaxes suitable to establish an empirical calibration (Muraveva et al. 2018; Neeley et al. 2019; Bhardwaj 2020). Therefore, NIR observations of abundant RR Lyrae in M3 will not only be useful for studies of the distance scale but also complement optical and ultraviolet data for a rigorous comparison with evolutionary and pulsation models.

In this work, we present NIR time-series observations of RR Lyrae in M3 for the largest sample of variables in an individual GC. This paper is organized as follows. In Section 2, we describe the observations, the data reduction, and the photometric calibrations. The NIR light curves and pulsation properties of the RR Lyrae are discussed in Section 3. We discuss the $JHK_s$-band PLRs for M3 RR Lyrae in Section 4 and estimate a robust distance to the cluster. The results are summarized in Section 5.

2. Observations, Data Reduction, and Photometric Calibration

2.1. Observations and Data Reduction

Our NIR observations were obtained using the WIRCam instrument (Puget et al. 2004) mounted on the 3.6 m Canada–France–Hawaii Telescope (CFHT) on the summit of Maunakea in Hawaii during four nights between 2019 May 26 and 29. WIRCam is an array of four 2048 × 2048 HgCdTe HAWAIIRG2 detectors arranged in a 2 × 2 grid with gaps of 45° between adjacent detectors. The pixel scale of each detector is 0.′3 pixel$^{-1}$ resulting in a field of view of ∼21′ × 21′. We requested $JHK_s$ time-series observations in queue mode centered on the M3 cluster center, and obtained 22 epochs in $J$ and 20 epochs in the $H$ and $K_s$ bands. Each epoch consisted of on average 15 dithered images obtained with an exposure time of 5 s per image. This resulted in more than 900 images in total. A summary of all of the epochs in the $JHK_s$ bands is listed in Table 1.

Images were downloaded from the IDL Interpreter of the WIRCam Images ("I′iwi10") preprocessing pipeline at CFHT. The "I′iwi pipeline incorporates detrending (dark subtraction, flat-fielding) and initial sky subtraction, and provides calibrated WIRCam data products. For each preprocessed image, a weight map was created using Weight-Matcher (Marmo & Bertin 2008) to mask bad pixels in the WIRCam mosaic. Astrometric calibration of preprocessed images was performed using SCAMP (Bertin 2006). SCAMP uses a catalog of sources matched with the Two Micron All Sky Survey (2MASS) Point Source Catalog (Skrutskie et al. 2006) generated using SExtractor (Bertin & Arnouts 1996).

The astrometric calibration was done at a very high precision both internally ($\sim$σint = 0.′1) and externally using 2MASS ($\sim$σext = 0.′15). SCAMP also scales the flux of each detector with different magnitude zero-points and performs an initial photometric calibration against 2MASS with an rms error of $\sim$0.025 mag for high signal-to-noise ratios (S/N > 100), and with an rms of $\sim$0.045 mag for fainter stars. After performing astrometric calibration, dithered images at each epoch were median-combined using SWARP (Bertin et al. 2002) at the instrument pixel scale.

2.2. Point-spread Function Photometry

We performed photometry on each epoch image using the DAOPHOT/ALLSTAR (Stetson 1987) and ALLFRAME (Stetson 1994) routines applied to the $J$, $H$, and $K_s$ filters separately. As a first step, we determined an approximate FWHM for sources in each image using IRAF.11 Using DAOPHOT, we identified all sources >4σ detection threshold and performed aperture photometry within 3 pixel apertures. In the second step, we selected up to 300 bright and isolated stars uniformly distributed across each image excluding sources in the inner 500 pixels from the crowded center of the cluster. These stars were selected to determine a point-spread function (PSF) for each image. The PSF was modeled as a Gaussian profile with no spatial variation across the detector. PSF photometry was performed using ALLSTAR on all sources for which aperture photometry was obtained in the first step. Finally, accurate frame-to-frame coordinate transformations were obtained for all epoch images using the DAOMATCH and DAOMASTER routines (Stetson 1993).

In the third step, we combined best-seeing (IQ < 0.5) $JHK_s$-band epoch images based on the FWHM to create a higher S/N reference frame. The first two steps were repeated

10 https://www.cfht.hawaii.edu/Instruments/Imaging/WIRCam/IiwiVersion2Doc.html
11 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.
and $D = -m_10^{-43}$.

| Date          | MJD      | J band | $N_i$ | H band | $N_i$ | K$_s$ band | $N_i$ |
|---------------|----------|--------|-------|--------|-------|------------|-------|
| 2019-05-26    | 58629.2882 | 1.037  | 0.60  | 15     |       |            |       |
| 2019-05-26    | 58629.2903 | 1.034  | 0.59  | 15     |       |            |       |
| 2019-05-26    | 58629.3412 | 1.015  | 0.78  | 15     |       |            |       |
| 2019-05-26    | 58629.3829 | 1.066  | 0.79  | 15     |       |            |       |
| 2019-05-26    | 58629.3873 | 1.076  | 0.72  | 15     |       |            |       |
| 2019-05-26    | 58629.4659 | 1.446  | 1.09  | 14     |       |            |       |
| 2019-05-27    | 58630.2506 | 1.109  | 0.53  | 15     |       |            |       |
| 2019-05-27    | 58630.2925 | 1.028  | 0.46  | 15     |       |            |       |
| 2019-05-27    | 58630.3369 | 1.014  | 0.71  | 15     |       |            |       |
| 2019-05-27    | 58630.3783 | 1.062  | 0.77  | 15     |       |            |       |
| 2019-05-27    | 58630.4223 | 1.197  | 0.59  | 15     |       |            |       |
| 2019-05-27    | 58630.4666 | 1.476  | 0.65  | 15     |       |            |       |
| 2019-05-28    | 58631.2576 | 1.083  | 0.72  | 15     |       |            |       |
| 2019-05-28    | 58631.3046 | 1.016  | 0.70  | 15     |       |            |       |
| 2019-05-28    | 58631.3475 | 1.023  | 0.74  | 15     |       |            |       |
| 2019-05-28    | 58631.3887 | 1.092  | 0.64  | 15     |       |            |       |
| 2019-05-28    | 58631.4323 | 1.258  | 0.71  | 15     |       |            |       |
| 2019-05-28    | 58631.4771 | 1.608  | 0.83  | 15     |       |            |       |
| 2019-05-29    | 58632.3011 | 1.018  | 0.89  | 16     |       |            |       |
| 2019-05-29    | 58632.3659 | 1.039  | 0.75  | 15     |       |            |       |
| 2019-05-29    | 58632.4045 | 1.148  | 0.60  | 15     |       |            |       |
| 2019-05-29    | 58632.4509 | 1.392  | 0.60  | 15     |       |            |       |
| 2019-05-29    | 58632.4952 | 1.294  | 0.57  | 15     |       |            |       |

Note. MJD: Modified Julian Date (JD−2,400,000.5). IQ: Image quality (in arcseconds) measured by the queued service observing at the CFHT. $N_i$: Number of dithered frames per epoch. ET: Exposure time (in seconds) for each dithered frame.

Table 1: Log of NIR Observations

Factors to obtain a common star list for each filter. Similarly, frame-to-frame coordinate transformations were also derived with respect to the reference frame for all epoch images. The reference star list was used as input for the PSF photometry in the ALLFRAME routine. Output photometry at each epoch was merged to obtain light curves and mean magnitudes in each filter for sources that were observed in at least 10 epochs. We also used Stetson’s TRIAL program to extract light curves of candidate variables and determine mean instrumental magnitudes and variability indices (Stetson 1996). The internal photometric precision of the $JHK_s$ magnitudes is shown as a function of 2MASS magnitude in Figure 1 after excluding sources in the most crowded central region of the cluster.

2.3. Photometric Calibration in the 2MASS System

The photometric catalogs in the $J$, $H$, and $K_s$ filters were matched and merged using DAOMATCH and DAOMASTER to perform the final photometric calibration. We found 1968 2MASS stars in our field of view and restricted the sample to stars with photometric quality flag “AAA.” This flag implies that the photometric measurements in all three $JHK_s$ bands are determined with an $S/N \gtrsim 10$. Sources located within 2′ from the crowded center were also excluded to avoid blended objects. Furthermore, the sample was limited to objects with 2MASS magnitudes fainter than 11 mag in the $JHK_s$ bands to avoid saturation and nonlinearities. After these restrictions, we cross-matched the merged catalog with the 2MASS stars and found 552 stars in common within a tolerance of 1″.

For absolute photometric calibration, we first corrected for a fixed magnitude-independent zero-point offset between 2MASS and instrumental magnitudes in the $JHK_s$ bands. Next, we solved for a color dependence by employing linear color terms in the transformations. Individual objects with residuals greater than 3σ from the initial fits were discarded iteratively to obtain robust transformations ($rms \sim 0.05$ mag for each fit in the $JHK_s$ bands). We found a statistical dependence on the 2MASS color term, but adding this extra parameter did not contribute to any significant reduction in the rms or the chi-squared per degree of freedom. Note that the majority of 2MASS standards span a relatively narrow range in color ($\Delta(J-K_s) \lesssim 0.8$ mag, $\Delta(H-K_s) \lesssim 0.4$ mag). Furthermore, the uncertainties in the 2MASS colors are significant (up to $\sim 0.15$ mag for quality flag “A”) while the uncertainties in the instrumental magnitudes are $5-10 \times$ smaller. We also derived transformations including instrumental color terms. No significant dependence on instrumental color term was found, and therefore, we did not apply any color corrections. We estimated a maximum uncertainty of $\lesssim 0.03$ mag in the photometry corresponding to the color range of RR Lyrae stars in common with 2MASS in our photometric catalogs.

2.4. M3 Photometry and Proper Motions

We cross-matched our NIR photometric catalog with the second data release from the Gaia mission (DR2; Lindegren et al. 2018), and found 27,417 objects for which proper motions and $G$-band photometry are available. The matching radius was set to 1″, and the nearest neighbor was adopted in case more than one was found within this radius. The top and middle panels of Figure 2 display the histograms of proper motions of stars within the WIRCam field of view. The histograms of proper motions along the R.A. and decl. peak at $\mu_R = 0.211$ and $\mu_\alpha = -2.385$ mas yr$^{-1}$ with a half-width at half-maximum of 1.129 and 0.752 mas yr$^{-1}$, respectively. The mean proper motions are consistent with those derived by Gaia.
Collaboration et al. (2018; \(m = -0.1\), \(m = -2.63\)) considering the large standard deviation of the Gaussian distribution. Given the uncertainties in the astrometry, we conservatively consider all sources within \(\pm 5\sigma\) of their peak proper motions as members of the cluster. Figure 3 displays the proper motion cleaned \(JHK_s\) color–magnitude diagram for sources in M3. The proper motions of RR Lyrae are shown in the bottom panel of Figure 2. The location of RR Lyrae on the horizontal branch is also shown in Figure 3 using mean magnitudes determined in the next section.

3. RR Lyrae Photometry

We adopted a reference list of variable candidates in M3 from the updated catalog of Clement et al. (2001). Their compilation consists of 241 RR Lyrae stars including coordinates, periods, V-band amplitudes, and the classification for most of these cluster variables. There are 178 RRab, 48 overtone-mode RR Lyrae (RRc), and 11 double/multimode (RRd) variables. Four RR Lyrae (V129, V217, V265, and V268) have uncertain classifications, and two of these (V265 and V268) do not have any determination of their pulsation period. Six of the 241 RR Lyrae variables (V113, V115, V123, V205, V206, and V299) are outside the WIRCam field of view. The periods and Oosterhoff and Blazhko types for these variables were updated following Jurcsik et al. (2015, 2017).

The \(JHK_s\) light curves of the RR Lyrae were extracted using a cross-match with PSF photometric catalogs within a search radius of 1.5. While 90% of targets matched within 0"1 tolerance, photometry for two RR Lyrae (V191 and V192) was retrieved with \(\sim 1"2\). We also computed periods for the well-sampled light curves and found good agreement with periods compiled by Clement et al. (2001). The latter periods were used to phase the light curves of all variables. Note that all mixed-mode variables were phased with their dominant first-overtone periods. We also determined a period of 0.5284 day for V265, which has no period listed in the catalog of Clement et al. (2001). However, our photometry of the

\[^{12}\text{http://www.astro.utoronto.ca/~cclement/}\]

\[^{13}\text{We exclusively use } A_{\lambda} \text{ to refer to the amplitudes in a given filter and not the extinction corrections.}\]

\[^{14}\text{V191 and V192 are located in the unresolved central 1/5 of the cluster, and their photometry is also contaminated.}\]
significantly blended V268 did not allow for a period determination for this variable, and therefore, it is excluded from our analysis. The final sample of RR Lyrae includes 234 stars (175 RRab, 48 RRc, and 11 RRd).

The light curves were fitted using a fourth-order Fourier sine series (e.g., Bhardwaj et al. 2015) to inspect their quality and determine phase differences (Δφ) between successive observations. Initially, light curves with a maximum of Δφ ≤ 0.2 and rms ≤0.05 mag with respect to the Fourier fits were assigned “A” quality flags while the remaining light curves were flagged as “B.” However, most RR Lyrae with periods 0.47 < P < 0.53 day exhibit larger phase gaps (Δφ > 0.2) either around mean-light or near the extrema. Therefore, Fourier-fitted light curves were also inspected visually and flagged as “A” if the extrema were well constrained so as to estimate accurate amplitudes. The poor-quality light curves that exhibit large scatter or do not show any distinct periodicity in one or more filters, due to photometric contamination, were assigned a “C” quality flag. Figure 4 displays a few example light curves of quality flags “A” and “B,” and different subclasses of RR Lyrae stars spanning the entire period range (see also Appendix A). NIR time-series photometry of M3 RR Lyrae is provided in Table 2.

3.1. Template Fits, Amplitude Ratios, and Mean Magnitudes

NIR light-curve templates are useful for estimating robust mean magnitudes for RR Lyrae having sparsely sampled light curves. New NIR templates for RRab and RRc stars were provided by Braga et al. (2019) covering three period bins (P ≥ 0.55, 0.55 < P < 0.7, and P ≥ 0.7 day) for RRab and a single period bin for all RRc stars. Initially, we fitted templates to RR Lyrae light curves with quality flag “A” solving for a phase offset and amplitude simultaneously. The peak-to-peak amplitudes were determined accurately with median uncertainties of 33, 28, and 30 mmag in the J, H, and Ks bands, respectively. These amplitude measurements are critical to constrain the amplitudes for the light curves having large phase gaps when combined with the known optical amplitudes, and to determine mean magnitudes.

Figure 5 displays NIR-to-optical amplitude ratios for RR Lyrae with well-sampled JHKs light curves. Braga et al. (2018) provided empirical evidence that NIR-to-optical amplitude ratios for the long-period (P ≥ 0.7 day) RRab in ω Cen are systematically larger than for the short-period (P < 0.7 day) RRab. In Figure 5, a similar trend is also seen for long-period (P ≥ 0.6 day) RRab in M3. The period at which this shift occurs is smaller for RRab in M3 than for those in ω Cen. The increase in the amplitude ratios for long-period (P ≥ 0.6 day) RRab is significant in the case of the H and Ks bands. Median values of NIR-to-optical amplitude ratios for short-period (P < 0.6 day) M3 RRab are identical to those for RRab (P < 0.7 day) in ω Cen in the case of A_H/A_V and A_Ks/A_V. For RRc in the J band and long-period (P ≥ 0.6 day) RRab, the median values are typically smaller for M3 variables compared to those of RR Lyrae in the ω Cen. Some of the Blazhko variables seem to be outliers in the amplitude ratio planes, but the dichotomy feature in amplitude ratios remains even if we exclude Blazhko variables. Furthermore, we found consistent results if the amplitudes were determined directly from the time-series data without template fits, but with a greater standard deviation. The mean values and the standard deviations of these amplitude ratios are listed in Table 3.

Figure 6 shows NIR amplitude ratios for RR Lyrae in M3. An increase in the median value of A_H/A_V and A_Ks/A_V for long-period RRab is also evident, similar to the result of Braga et al. (2018). This feature of amplitude ratios involving NIR data is different to the behavior of optical amplitude ratio (A_V/A_I) for M3 RRab (Jurcsik et al. 2018), which is constant over the entire period range (see Braga et al. 2015, for ω Cen RRab). While this dichotomy is apparent for RRab in the GCs, Jurcsik et al. (2018) instead provided empirical evidence of a linear increase in A_Ks/A_V as a function of period for RRab in the Galactic bulge. The dichotomy in RRab amplitude ratios is observed in GCs of two different Oosterhoff types (M3—OoI and ω Cen—OoII) and different metallicity distributions (significant spread in ω Cen versus negligible spread in M3). Therefore, it is unlikely that metallicity is playing an important role. However, the observed period shift in the break period (log(P) = −0.222 [day] for M3 versus log(P) = −0.155 [day] for ω Cen) in NIR-to-optical amplitude ratios is in excellent agreement with the offset between the mean periods of their RRab stars (Δ log(P_{RRab}) = −0.066 [day]). This hints that the break period in the amplitude ratios involving NIR data is also an indicator of the Oosterhoff type of the cluster. Further investigation is needed to confirm the feature in the amplitude ratios and understand the cause of the dichotomy.
Finally, NIR templates were fitted to the light curves using the NIR-to-optical amplitude ratios listed in Table 3 for M3 RR Lyrae allowing for variations within 1σ of the quoted uncertainties. We used three period bins (P ≤ 0.54, 0.54 < P < 0.6, and P ≥ 0.6 day) for RRab in contrast to Braga et al. (2018). The choice of these adopted period cuts was based on the empirical result of the amplitude ratios and the variations in the light-curve parameters of RRab in M3 at these periods (Jurcsik et al. 2017). The Fourier amplitude parameter (R21) in the V band starts to decrease as a function of period ∼0.6 day onwards, and the phase parameter (ϕ21) exhibits a sudden increase for P > 0.54 day (see Figure 6 of Jurcsik et al. 2017). The lower-order Fourier parameters contain the most characteristic information about the shape of the light curves (Simon & Lee 1981; Bhardwaj et al. 2015, 2017a; Das et al. 2018).

The mean magnitudes were estimated through numerical integration of the best-fitting templates. While the uncertainties in the mean magnitudes from the template fits were typically <0.01 mag, we conservatively added the median photometric error in the individual measurements to the uncertainties in the mean magnitudes. For multimode variables and light curves with quality flag “C,” weighted mean magnitudes were simply determined from the multi-epoch measurements. The peak-to-peak amplitudes were also determined from the template fits for RR Lyrae with quality flag “B.” The NIR pulsation properties, mean magnitudes, and amplitudes are tabulated in Table 4.

We compared our mean magnitudes with those from Longmore et al. (1990). The magnitudes from Longmore et al. (1990) were in the Anglo-Australian Observatory (AAO)
Figure 5. NIR-to-optical amplitude ratios, $A_r/A_V$ (top), $A_U/A_V$ (middle), and $A_K/A_V$ (bottom) are plotted as a function of the logarithmic period. The median value and the standard deviation ($M \pm \sigma$), and the number of stars for each sample of RRc, short-period ($P < 0.6$ day) RRab, and long-period ($P > 0.6$ day) RRab are also shown in each panel. The solid and dashed lines represent the median and $\pm 1\sigma$ standard deviation of each sample. RR Lyrae stars known to display the Blazhko effect are shown using filled symbols. Representative median error bars are also shown at the bottom of each panel.

Figure 6. The same as Figure 5 but for the NIR amplitude ratios, $A_r/A_h$ (top) and $A_K/A_h$ (bottom). Median error bars are of the order of the symbol size.

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Table 3

| Band    | RRc    | RRab (S) | RRab (L) |
|---------|--------|----------|----------|
|         | Mean   | $\sigma$ | Mean     | $\sigma$ | Mean     | $\sigma$ |
|         | $A_r$  | $A_U$    | $A_K$    | $A_r$    | $A_U$    | $A_K$    | $A_r$    | $A_U$    | $A_K$    | $A_r$    | $A_U$    | $A_K$    |
| All RR Lyrae with Quality Flag “A” |       |          |          |          |          |          |          |          |          |          |          |          |
| $A_r/A_V$ | 0.357  | 0.042    | 0.391    | 0.071    | 0.419    | 0.071    |          |          |          |          |          |          |
| $A_U/A_V$ | 0.237  | 0.043    | 0.281    | 0.050    | 0.373    | 0.071    |          |          |          |          |          |          |
| $A_K/A_V$ | 0.222  | 0.035    | 0.278    | 0.049    | 0.361    | 0.074    |          |          |          |          |          |          |
| $A_r/A_h$ | 0.671  | 0.110    | 0.721    | 0.075    | 0.891    | 0.110    |          |          |          |          |          |          |
| $A_U/A_h$ | 0.620  | 0.086    | 0.720    | 0.081    | 0.854    | 0.139    |          |          |          |          |          |          |
| $A_K/A_h$ | 0.355  | 0.041    | 0.412    | 0.042    | 0.439    | 0.065    |          |          |          |          |          |          |
|         | 0.235  | 0.043    | 0.294    | 0.036    | 0.389    | 0.063    |          |          |          |          |          |          |
|         | 0.667  | 0.107    | 0.701    | 0.057    | 0.897    | 0.118    |          |          |          |          |          |          |
|         | 0.621  | 0.084    | 0.704    | 0.059    | 0.844    | 0.154    |          |          |          |          |          |          |

Note. Mean and standard deviation ($\sigma$). RRab (S): Short-period RR Lyrae ($\log(P) < 0.6$) day. RRab (L): Long-period RR Lyrae ($\log(P) > 0.6$) day.

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Photometric system. For a relative comparison, the photometric transformations from Carpenter (2001) are used to convert AAO magnitudes to the 2MASS system. These transformations also require a $(J-K)_AAO$ color term that has a coefficient of $-0.01$ dex. Since $J$-band magnitudes were not provided by Longmore et al. (1990), we adopt a median $(J-K)$ color for the RR Lyrae in our sample. Given the small coefficient of the $(J - K)_AAO$ color term, any deviation from the mean value within the RR Lyrae color range does not make any significant difference to the $K$-band magnitudes. Figure 7 shows the difference in the $K$-band photometry as a function of the radial distance from the center of the cluster. While several common stars show large offsets ($>0.1$ mag), no statistically significant difference can be determined given the scatter around the median value.

3.2. Color–Magnitude and Bailey Diagrams

We used the mean magnitudes and amplitudes estimated from the best-fitting templates to study the pulsation properties of RR Lyrae at NIR wavelengths. Figure 8 displays the color–magnitude diagrams in $J - H$, $J$ and $J - K_s$, $K_s$ for RR Lyrae in M3. The intrinsic color variations in the NIR bands are significantly ($\sim3-4\times$) smaller than in the optical bands. The RRab and RRc pulsators overlap in the so-called “OR” region (Bono et al. 1997) where both pulsation modes are possible. Most Blazhko RR Lyrae are also located centrally along the overlapping region between RRab and RRC. In both color–magnitude diagrams, a few RR Lyrae that appear to be located farther from the concentrated cluster of sources are marked. Most of these exhibit large photometric uncertainties in at least one filter.

In Figure 8, the theoretically predicted fundamental-mode red edge and the first-overtone blue edge from Marconi et al. (2015) are also overplotted in the $(J - K_s)$, $K_s$ color–magnitude diagram. Most NIR observations fall in the region within the predicted boundaries of the instability strip while some RR Lyrae are

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https://www.astro.caltech.edu/~jmc/2mass/v3(transformations/)
| ID   | R.A.    | Decl.   | Period | Type   | Mean magnitudes (mag) | $\sigma_{\text{mag}}$ | Amplitudes ($A_\lambda$) (mag) | $\Delta^\ast$ (arcsec) | QF | 
|------|---------|---------|--------|--------|-----------------------|-----------------------|-----------------------------|------------------------|----|
| V1   | 205.546333 | 28.342722 | 0.52059 | RRab   | 14.880 14.647 14.594 | 0.017 0.019 0.020 | 0.419 0.311 0.317 | 0.006 | AI |
| V3   | 205.565458 | 28.361611 | 0.55818 | RRab   | 14.916 14.636 14.607 | 0.019 0.023 0.024 | 0.416 0.344 0.325 | 0.015 | BII, Bl |
| V4a  | 205.534125 | 28.375972 | 0.38504 | RRab   | 14.623 14.330 14.263 | 0.028 0.036 0.030 | 0.341 0.270 0.213 | 0.016 | B |
| V4s  | 205.534250 | 28.375889 | 0.59305 | RRab   | 14.766 14.509 14.609 | 0.029 0.036 0.033 | 0.443 0.304 0.274 | 0.453 | B |
| V5   | 205.630375 | 28.372417 | 0.50579 | RRab   | 14.881 14.682 14.662 | 0.015 0.015 0.018 | 0.557 0.386 0.350 | 0.008 | AI, Bl |
| V6   | 205.508667 | 28.394889 | 0.51434 | RRab   | 14.968 14.752 14.679 | 0.020 0.021 0.022 | 0.438 0.275 0.272 | 0.006 | BI |
| V7   | 205.546208 | 28.402833 | 0.49742 | RRab   | 15.008 14.761 14.736 | 0.020 0.024 0.022 | 0.532 0.325 0.287 | 0.008 | BI, Bl |
| V8   | 205.522083 | 28.371889 | 0.63671 | RRab   | 14.456 14.300 14.255 | 0.023 0.027 0.024 | ... ... ... | ... | C, Bl |
| V9   | 205.456292 | 28.320361 | 0.54155 | RRab   | 14.862 14.622 14.561 | 0.016 0.020 0.018 | 0.469 0.314 0.294 | 0.004 | AI |
| V10  | 205.596250 | 28.416833 | 0.56955 | RRab   | 14.824 14.567 14.515 | 0.017 0.017 0.017 | 0.437 0.296 0.319 | 0.004 | AI, Bl |
| V11  | 205.499917 | 28.319944 | 0.50789 | RRab   | 14.874 14.664 14.604 | 0.015 0.015 0.017 | 0.518 0.240 0.219 | 0.007 | BI |

Note. Star ID, coordinates (epoch J2000), periods, and subtypes are taken from Clement et al. (2001). $\Delta^\ast$ is the separation, in arcseconds, between coordinates of RR Lyrae from Clement et al. (2001) and our astrometric calibration. Quality flags (QF)—“A,” “B,” and “C” (see the text); “I” and “II” represent Oosterhoff types I and II, respectively; “Bl” indicates Blazhko variation. Photometric pulsation properties of V297 are also included for completeness.

(This table is available in its entirety in machine-readable form.)
Figure 7. Difference in $K$-band mean magnitudes between our photometry and that of Longmore et al. (1990) as a function of the radial distance from the cluster center. TW: this work. The median value and the standard deviation are also shown.

Figure 8. NIR color–magnitude diagrams in $(J - H)$, $J$ (top) and $(J - K_s)$, $K_s$ (bottom) for the horizontal branch RR Lyrae. Note that one of the RR Lyrae (V297) is not shown (see Figure 3). In the bottom panel, the dotted blue and dashed red lines display the theoretically predicted first-overtone blue edge and the fundamental red edge from Marconi et al. (2015). Some RR Lyrae that appear to be located farther from the majority of the variables are marked in each panel, and their error bars are also shown. Representative median error bars are also shown at the bottom right of each panel.

redder/bluer than the fundamental/first-overtone edges. Extinction corrections are not applied to the color–magnitude diagrams because the reddening, $E(B - V) = 0.01$ mag, in M3 is negligible (Harris 2010). Nevertheless, the outlier RR Lyrae stars will fall inside the predicted boundaries of the instability strip within $\pm 3\sigma$ of their quoted uncertainties. While the predicted topology of the instability strip may be independent of the metal abundance in the NIR bands, note that the model computations also have a typical minimum resolution of $\pm 50$ K in effective temperature (Marconi et al. 2015).

Figure 9 shows the period–amplitude or Bailey diagrams in the $JHK_s$ bands for M3 RR Lyrae variables for the first time. The left panels display Bailey diagrams based on amplitudes determined accurately from the well-sampled light curves. In the $J$ band, the amplitudes of the RRab decrease as a function of increasing period, similar to the situation in the optical bands (see Figure 1 of Jurcsik et al. 2017). The right panels show Bailey diagrams for light curves with both quality flags “A” and “B.” The loci of OoI and OoII type RRab were determined by fitting second-order polynomials to $J$-band amplitudes in the period range $-0.3 < \log(P) < -0.1$ day, and the following equations were obtained:

$$A_{J,\text{OoI}} = -1.27(0.09) - 11.59(0.70)\log(P) - 19.47(1.40)\log(P)^2,$$

$$A_{J,\text{OoII}} = -0.62(0.16) - 8.93(1.88)\log(P) - 17.97(5.31)\log(P)^2.$$

The locus of OoI RRab stars is consistent with the scaled optical band locus for RR Lyrae in M3 from Cacciari et al. (2005; see top left panel of Figure 9). The mean period offset between our empirical OoI and OoII loci is also consistent with the observed shift in the break period in the RRab amplitude ratios in M3 and ω Cen. The $J$-band loci were scaled arbitrarily by 75% and 65% in the $H$ and $K_s$ bands to provide a relative comparison of amplitudes with different quality flags. The majority of amplitudes for RRab that were determined from the light curves with quality flag “B” fall below the locus of OoI types. This suggests that the amplitudes for the light curves with large phase gaps are likely underestimated because the NIR-to-optical amplitude ratios, used to constrain the amplitudes, exhibit a scatter of $\sim 20\%$ around the mean values. Furthermore, the $V$-band amplitudes of Blazhko RR Lyrae in M3 can change by $\Delta V = 0.65$ mag, and exhibit a relative change of up to 90% in total amplitude (Jurcsik et al. 2017). Therefore, the amplitude estimates are likely uncertain in these cases.

At NIR wavelengths, Braga et al. (2018) found evidence that the locus of RRab stars starts to flatten for longer periods while Gavrilchenko et al. (2014) found a nearly flat locus of RRab at mid-infrared wavelengths. In Figure 9, the range of amplitudes for RRab in the $H$ and $K_s$ bands is smaller than in the $J$ band and exhibits more scatter. However, no evidence of flatness is noted. Instead a steady decrease in amplitudes is seen for longer-period RRab stars. The light curves of RRc are nearly sinusoidal with smaller variability amplitudes, and therefore, the amplitudes are well constrained even for light curves with poor phase coverage. Furthermore, no obvious trend is seen in the amplitudes as a function of the radial distance from the cluster center. For low amplitude RRc stars with $A_V < 0.1$ mag, the precision of our photometry is insufficient to detect variability in NIR, which has a smaller amplitude than in optical bands. RR Lyrae variables with known Blazhko modulations (Jurcsik et al. 2015, 2017) are also overplotted in Figure 9. No obvious trend is seen between Blazhko and non-Blazhko variables unlike in optical bands where Blazhko stars typically exhibit smaller amplitudes at a given period. This is expected in the NIR where no significant amplitude modulations are seen (Jurcsik et al. 2018), but observations sampled
over a long time interval are needed to notice these long-term variations.

4. Period–Luminosity Relations

We used the mean magnitudes listed in Table 4 to derive PLRs for M3 RR Lyrae at NIR wavelengths. The reddening in M3 is small: \( E(B - V) = 0.01 \) mag (Harris 2010), 0.013 mag (VandenBerg et al. 2016). Adopting the reddening law of Cardelli et al. (1989) and a total-to-selective absorption ratio \( R_V = 3.23 \), the extinction in the \( V \) band amounts to \( \sim 0.04 \) mag. Therefore, extinction corrections of 13, 9, and 5 mmag were estimated in the \( J \), \( H \), and \( K_s \) bands, respectively, using total-to-selective absorption ratios from Bhardwaj et al. (2017b).

Under the basic assumption that the PLRs are linear over the entire period range under consideration, the following relation was fitted to the data:

\[
m_{\lambda} = a_{\lambda} + b_{\lambda} \log(P),
\]

where \( a_{\lambda} \) and \( b_{\lambda} \) give the slope and zero-point of the PLR in a given filter. The scatter (rms) in the PLR mainly results from the intrinsic width in temperature of the instability strip, a metallicity contribution (\( \sim -0.18 \) mag dex in the \( K_s \) band; Marconi et al. 2015), and uncertainties in the extinction correction. However, the extinction correction uncertainties are minimal in NIR bands, and high-resolution spectra of bright stars show that M3 has no appreciable spread in metallicity (\( \sigma_{[Fe/H]} = 0.03 \) dex; Sneden et al. 2004).

We considered three different samples of RR Lyrae to derive PLRs: (1) RRab variables; (2) a combined sample of RRc and RRd, where dominant first-overtone periods are used for the latter; and (3) a combined sample of RRab, RRc, and RRd variables after fundamentalizing overtone periods using \( \log(P_{FU}) = \log(P_{FO}) + 0.127, \) where “FU” and “FO” represent fundamental and first-overtone modes, respectively. Note that five RR Lyrae with periods shorter than \( \sim 0.297 \) day are pulsating in the second-overtone mode (see Table 1 of Jurcsik et al. 2015).

Figure 10 displays \( JHK_s \)-band magnitudes for the RR Lyrae in M3 plotted as a function of the logarithm of their pulsation periods. We fitted a linear regression in the form of Equation (2) iteratively removing the single largest \( > 3\sigma \) outlier.
in each filter separately until convergence. The best-fitting PLRs are also shown in Figure 10, and the results of the regression analysis are listed in Table 5. The scatter in the empirical JHKσ-band PLRs is consistently \( \lesssim 0.05 \) mag, which is up to twice as small as that in the optical RI-band PLRs. Adopting a smaller sigma-clipping threshold (\( \sim 2 \sigma \)), the scatter in these relations is only limited to the photometric uncertainties while allowing us to retain \( \sim 75\% \) of RR Lyrae within this threshold. We also investigated possible variations in the slopes and zero-points of the PLRs for samples with light-curve quality flags “A” and “B,” and found no statistically significant differences from the values quoted in Table 5. Furthermore, we also found consistent results in terms of the slopes and zero-points of the PLRs after excluding: (1) Blazhko stars, (2) second-overtone-mode variables, (3) stars within 1/5 radius from the center of the cluster, and (4) stars within a period bin of \( \log(P) = 0.05 \) day at either end of the period distribution under consideration.

Figure 11 shows the residuals of the JHKσ-band PLR fits plotted against the logarithm of the pulsation period. We do not observe any distinct trend in the residuals of the PLRs except that the majority of RRab stars with periods close to 0.5 day exhibit positive residuals in the J band. On the other hand, the majority of RRc stars in the overlapping period range seem to exhibit negative residuals. Note that RRab stars with periods close to 0.5 day also exhibit large phase gaps due to the observing cadence. This can lead to an offset in their mean magnitudes if the amplitudes of the template fits are not well constrained. The residuals of the PLRs for RR Lyrae, which are located in the central 1/5, are also consistent with zero-mean. However, these residuals exhibit standard deviations (\( \sim 0.09 \) mag) up to two times larger than for those in the outer regions. Furthermore, some of the outliers with the largest residuals (including V143) are also known to exhibit Blazhko effects. A discussion about individual RR Lyrae including outliers in the PLRs is given in Appendix B.
We also compared the residuals of the PLRs against the spectroscopic metallicities provided by Sandstrom et al. (2001) for 27 RRab variables in common. Sandstrom et al. (2001) determined metallicities using iron lines from moderate-resolution spectra and found a mean [Fe/H]$_{FeI}$ = -1.22 dex with a standard deviation of 0.12 dex. However, the median uncertainties in their measurements are of the order of 0.15 dex, and the metallicity range is minimal (Δ[Fe/H] $\sim$ 0.36 dex) given the uncertainties. We do not observe any obvious trend in the residuals against the metallicity, which is expected as high-resolution spectra of bright giants do not provide any evidence of a significant spread in the mean metallicity of M3 (Sneden et al. 2004).

Finally, we also compared the slopes of the NIR PLRs of RR Lyrae in GCs as shown in Figure 12. A well-known trend in the slopes of NIR PLRs, which become steeper when moving from the $J$ to $K_s$ bands (Neeley et al. 2017; Beaton et al. 2018; Bhardwaj 2020), is also seen for M3 RR Lyrae variables. The slopes of the $JHK_s$-band PLRs are consistent with those for RR Lyrae in the GCs with different mean metallicities ([Fe/H] = -1.50 in M3; -1.16 in M4, -1.29 in M5; Harris 2010), and in the GC with a significant spread in metallicity (ω Cen; Braga et al. 2018). Furthermore, our PLR slopes for samples of RRab and all RR Lyrae are in good agreement with theoretically predicted PLZ relations ($J$: -1.98 (RRab), -1.90 (all); $H$: -2.24 (RRab), -2.22 (all); $K_s$: -2.27 (RRab), -2.25 (all); Marconi et al. 2015). The PLR slopes for RRc stars are shallower than the theoretical predictions in all three bands but statistically consistent given the larger uncertainties.

### 4.1. Distance to the M3 Cluster

New NIR photometry of RR Lyrae in M3 provides an opportunity to estimate a robust distance to the cluster thanks to the precision and accuracy of the mean magnitudes and derived PLRs. However, an absolute calibration of NIR PLRs of RR Lyrae is still lacking, and the precision of the estimated distances is mainly affected by the zero-point uncertainties of the calibrator relations (Beaton et al. 2018; Muraveva et al. 2018; Bhardwaj 2020). Theoretical models predict a significant metallicity dependence of the NIR PLRs (Catelan et al. 2004; Marconi et al. 2015), but some empirical relations also suggest a marginal or weaker dependence on metallicity (Sollima et al. 2006; Muraveva et al. 2015). Note that theoretical calibration has been preferred in the most recent studies on distance determination using infrared observations of RR Lyrae (e.g., Neeley et al. 2017; Braga et al. 2018).

First, we also adopted the theoretical calibrations of the RR Lyrae PLZ relation in the $JHK_s$ bands from Marconi et al. (2015). Given that the metallicities in these predicted relations...
are on the Carretta & Gratton (1997) scale, an iron abundance of [Fe/H] = −1.34 dex is adopted for M3. Marconi & Degl’Innocenti (2007) also modeled the light curves of RR Lyrae in M3 for [Fe/H] = −1.3 dex, which led to a metal abundance Z ≈ 0.001, and estimated a distance modulus to the cluster, \( \mu = 15.10 \pm 0.10 \) mag. The slope and metallicity coefficients of the predicted relations were used to anchor the absolute zero-point of the JHK\(_c\)-band PLRs and to determine a distance modulus to the M3 cluster. The results of distance measurements using JHK\(_c\)-band PLRs are tabulated in Table 6. Distance moduli based on J-band PLZ relations are comparatively larger than for the \( H \) and \( K_s \) bands, possibly due to differences in the slopes and a relatively larger dispersion in the photometry and uncertainties in the coefficients of the predicted relations. For systematic uncertainties, errors in the zero-points, errors in the slopes propagated through the difference of the predicted relations. For systematic uncertainties, errors in the zero-points, errors in the slopes propagated through the difference of the predicted relations. For systematic uncertainties, errors in the zero-points, errors in the slopes propagated through the difference of the predicted relations.

This is expected since no metallicity term is included in the PLRs in Table 5, and on average the five Galactic RR Lyrae with the HST parallaxes are more metal poor ([Fe/H] ~ −1.63 dex; Bhardwaj et al. 2016, see Table 8) than the mean metallicity of M3. Accounting for the metallicity term according to the predicted PLZ relations, the distance measurements based on empirical relations also become consistent with the value obtained using theoretical calibrations. However, Neeley et al. (2017) suggested that the HST parallaxes for the calibrator RR Lyrae and their reddening values in the literature may be affected by systematics, in particular for RR Lyr and UV Oct. Indeed, the parallax of RR Lyr yields the largest distance modulus to M3 despite having [Fe/H] = −1.39 dex, which is more consistent with M3.

We also used an empirical calibration of the PLZ\(_K_s\) relation listed in Table 4 of Muraveva et al. (2018).
5. Summary

We have presented new NIR time-series observations of a 21' × 21' sky area around the center of the M3 globular cluster. Our sample of RR Lyrae in M3 was adopted from the catalog of Clement et al. (2001), and uses accurate pulsation periods and V-band amplitudes from the extensive optical photometric studies in the literature (for example, Jurcsik et al. 2015, 2017). The ensemble NIR photometry from multi-epoch observations was derived and calibrated with an internal photometric precision of better than 2% for RR Lyrae in moderately crowded regions. Combining optical and NIR data resulted in the largest sample to date of 233 RR Lyrae in a single cluster with multi-epoch JHKs-band data. We used light-curve data to investigate amplitude ratios and Bailey diagrams for RR Lyrae in the JHKs bands for the first time in M3. New templates for RR Lyrae in NIR from Braga et al. (2018) were used to determine precise photometric mean magnitudes in the JHKs bands and derive new PLRs. Our precise PLRs will be useful in investigating the dependence on metallicity when complemented with literature data of homogeneous RR Lyrae populations in the GCs having independent distances and different mean metallicities.

We summarize our main results as follows:

1. We presented JHKs-band light-curve data for 233 RR Lyrae variables in the M3 cluster with an average of 20 epochs in each filter. The M3 RR Lyrae sample consists of 175 RRab, 47 RRc, and 11 RRd variables with JHKs-band time series for the first time. It also provides a five-fold increase in the sample size of M3 RR Lyrae with Ks-band mean magnitudes available in the literature.

2. NIR-to-optical amplitude ratios for RR Lyrae in M3 display a systematic increase moving from RRC to short-period (P < 0.6 day) and long-period (P < 0.6 day) RRab variables. A similar trend is also observed in the amplitude ratios (Δ HKs/Δ J) involving only NIR bands. The shift in the median values of the amplitude ratios for long-period RRab occurs at an earlier period for M3 variables than for those in the ω Cen. This observed shift in the break period (Δ log(P) = −0.067 [day]) is in excellent agreement with the difference between the mean RRab periods in the two distinct Oosterhoff type clusters (Oof M3 and OoII ω Cen).

3. The largest sample of RR Lyrae (or RRab) in a single cluster is used to derive new JHKs-band PLRs. Our sample of 175 RRab stars encompasses almost twice the number of fundamental pulsators in ω Cen with time-series NIR photometry (Braga et al. 2018). The residuals of these empirical relations do not display any trend as a function of metallicity, suggesting that the spread in metallicity of individual M3 RR Lyrae is negligible.

4. The slopes of empirical JHKs-band PLRs for M3 RR Lyrae are in excellent agreement with the slopes of PLRs for RR Lyrae in GCs with different mean metallicities. Furthermore, our PLRs for RRab and the combined sample are also consistent with the theoretical predictions of the PLZ relations from Marconi et al. (2015). While PLRs for RRc stars are shallower than the theoretical predictions, they are also in agreement within the uncertainties.

5. We used predicted RR Lyrae PLZ relations with a chemical abundance of Z = 0.001, Y = 0.25, to determine a distance modulus to M3 of μ = 15.041 ± 0.017 (stat.) ± 0.036 (syst.) mag. Our distance estimate is in very good agreement with distances determined based on modeling of M3 RR Lyrae (Marconi & Degl’Innocenti 2007) or the Baade–Wesselink method (Jurcsik et al. 2017). We also found consistent distance estimates based on the zero-point calibration using HST or Gaia parallaxes for RR Lyrae provided a proper account of metallicity effects is taken.

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Facility: CFHT (WIRCam Near-infrared imager).

Software: IRAF (Tody 1986, 1993), DAOPHOT/ALLSTAR (Stetson 1987) DAOMATCH and DAOMASTER (Stetson 1993), ALLFRAME (Stetson 1994), Sextractor (Bertin & Arnouts 1996), SWARP (Bertin et al. 2002), SCAMP (Bertin 2006), WeightWatcher (Marconi & Bertin 2008), IDL (Landsman 1993), Astropy (Astropy Collaboration et al. 2013).

Appendix A

Additional Figures

NIR light curves of a few randomly selected M3 RR Lyrae with different quality flags are shown in Figures 13 and 14. Time-series data is available online as supplementary material for RR Lyrae in M3.
Figure 13. Example $JHK_s$-band light curves of RR Lyrae with quality flag "A" in our sample. The $J$- (blue stars) and $K_s$-band (red circles) light curves are offset for clarity by +0.1 and −0.2 mag, respectively. The dashed lines represent the best-fitting templates to the data in each band. Star ID, subtype, and the pulsation period are included at the top of each panel.
Figure 14. The same as Figure 13 but for the RR Lyrae with light-curve quality flag “B.”
Appendix B

Comments on a Few RR Lyrae Variables

V4s and V4n: These are two RR Lyrae with similar periods that are separated by 0"/45, and good-quality light curves for both variables were obtained. V4n is significantly brighter than the best-fitting PLRs. Since the JHKs amplitudes of V4n are up to 23% smaller than those for V4s, it is likely that photometry of this RR Lyrae is biased by a few epochs obtained in relatively poorer seeing due to blending with nearby stars.

V8, V159, V259: These RR Lyrae are brighter than the best-fitting PLRs in at least one filter. Photometry of these objects is blended due to bright sources in close proximity. J- and Ks-band light curves of V8 display clear periodicity, but H-band photometry is significantly contaminated. V159 is an outlier only in the H band, although there it exhibits a more periodic light curve than in the JKs bands.

V48 and V43: We recovered a high-quality light curve for V43 with full phase coverage despite it being located within the cluster’s unresolved central 1/5 region, and the cause of this Blazhko RR Lyrae being brighter than the PLRs is not clear. Similarly, V48 is also brighter than the PLRs, although it is well resolved, and the light curves are well sampled in the JHKs bands.

V129, V217, V234: We have confirmed the uncertain classification of these variables listed in the catalog of Clement et al. (2001). V129 is an RRc while V217 is an RRab variable. V234 is marked as a candidate field star, but its mean magnitudes are consistent in the JHKs-band PLR plane, and therefore, it is likely a cluster member.

V148, V181, V242, V246, and V261: These RR Lyrae have proper motions beyond ±5σ of their mean values and exhibit (except for V261) residuals that are consistent within ±2σ in all three JHKs filters.

V192, V244, and V298: The light curves do not exhibit any periodicity, but the weighted mean magnitudes are consistent with the best-fitting JHKs-band PLRs. V244 exhibits large scatter in the time series, and the residuals of the JH-band PLRs are also large (>0.1 mag). Similarly, individual measurements for V298 also exhibit large photometric uncertainties.

V220, V251, and V253: The light curves of these RR Lyrae display periodicity despite large scatter, and the mean magnitudes are consistent with the best-fitting PLRs.

V265: We derived a period (0.5284 day) for the first time and confirm that it is an RR Lyrae variable. It is classified as RRab, and JHKs-band mean magnitudes are consistent with RR Lyrae PLRs. Photometry is severely blended for another close companion, V268, preventing us from obtaining any estimate of the pulsation period.

V297: This is an obvious outlier in the proper motions, color–magnitude diagrams, and the period–luminosity planes. We also looked at the 2MASS magnitudes for this object and found that it is more than one magnitude brighter in the JHKs bands than the horizontal branch RR Lyrae with similar periods. V297 is also significantly redder (B − V = 0.97 mag) than horizontal branch stars in the optical color–magnitude diagram (Hartman et al. 2005, their Figure 8 and Table 2). Since the V-band amplitude of V297 is very small (0.05 mag; Hartman et al. 2005), no periodic variability is recovered in our photometry. It is located in the outskirts of the cluster and is unlikely blended, suggesting that it is either misclassified as an RR Lyrae or it may be a field variable. Therefore, we do not consider V297 a member of the cluster RR Lyrae population.
