Absolute Magnitudes and Colors of RR Lyrae Stars in DECam Passbands from Photometry of the Globular Cluster M5

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Abstract

We characterize the absolute magnitudes and colors of RR Lyrae stars in the globular cluster M5 in the ugriz filter system of the Dark Energy Camera (DECam). We provide empirical period–luminosity (P–L) relationships in all five bands based on 47 RR Lyrae stars of the type ab and 14 stars of the type c. The P–L relationships were found to be better constrained for the fundamental-mode RR Lyrae stars in the riz passbands, with dispersions of 0.03, 0.02 and 0.02 mag, respectively. The dispersion of the color at minimum light was found to be small, supporting the use of this parameter as a means to obtain accurate interstellar extinctions along the line of sight up to the distance of the RR Lyrae star. We found a trend of color at minimum light with a pulsational period that, if taken into account, brings the dispersion in color at minimum light to ≤0.016 mag for the $(r-i), (i-z)$, and $(r-z)$ colors. These calibrations will be very useful for using RR Lyrae stars from DECam observations as both standard candles for distance determinations and color standards for reddening measurements.

Key words: dust, extinction – globular clusters: individual (M5) – stars: distances – stars: variables: RR Lyrae

Supporting material: figure set, machine-readable tables

1. Introduction

RR Lyrae stars are well established standard candles and tracers of old stellar populations throughout the Local Group. They are also extremely good standard colors. As first demonstrated by Sturch (1966), the colors of fundamental-mode RR Lyrae stars near the minimum light phase of their pulsation cycle are predictable with accuracies of a few percent. As such, they broadcast both their distance as well as their line-of-sight reddening, and hence extinction. This property makes RR Lyrae stars especially good probes in regions of high interstellar extinction such as the Galactic center and inner Bulge, where they exist in large numbers. There is a rich history of attempts to study aspects of the inner Galaxy using RR Lyrae stars (Baade 1946; Plaut 1968, 1970, 1973; Blanco 1984, 1992a; Alcock et al. 1998; Kunder & Chaboyer 2008; Gran et al. 2016, among others). The most recent and extensive photometric catalogs have come from the OGLE project (e.g., Udalski et al. 2015). Their RR Lyrae survey results are described in Pietrukowicz et al. (2015). Relative to these past investigations, the Dark Energy Camera (DECam, Flaugher et al. 2015) on the Blanco 4 m telescope offers a more extensive chromatic coverage, allowing us to measure colors over a wide spectral range. This enables us to not only measure reddening to the RR Lyrae stars accurately, but also to examine alleged variations in the reddening law toward the Galactic center. In addition to simply acquiring a more accurate map of the RR Lyrae stars’ spatial distribution (and by extension that of the “ancient” stellar population), the relatively high density of RR Lyrae stars in these regions offers a chance to make an accurate map of the line-of-sight extinction through the foreground disk that depends only upon our knowledge of RR Lyrae star colors. This should be an improvement over prior methods such as using colors of red clump stars, which are much more sensitive to stellar population parameters such as metallicity. If the goal is to examine the stellar populations in the bulge and bar using color–magnitude and Hess diagrams, it is desirable to correct for reddening using a probe like RR Lyrae star minimum light colors, which as we discuss later, is known to be insensitive to metallicity.

To exploit this opportunity, we must first determine empirically the intrinsic colors of the RR Lyrae stars at minimum light in the photometric system of the DECam passbands. Because the globular cluster M5 (NGC 5904) is a well studied cluster rich in RR Lyrae stars (Clement et al. 2001, and references therein) and is located toward the southern Galactic cap with minimal line-of-sight reddening, its RR Lyrae stars are ideal for establishing baseline colors and absolute magnitudes that can be used to interpret photometry of reddened RR Lyrae stars toward the Galactic center and along or near the plane of the Galaxy. The characteristics of M5, including distance and reddening, are summarized in Harris (1996). In this paper, we present results from DECam photometry of M5 RR Lyrae stars to establish their colors at minimum light and absolute magnitudes in the DECam passbands, which are needed to determine the extinction toward the stars and their distances. In upcoming papers, we will use these results as established baseline properties of RR Lyrae stars to study the Galactic Bulge. We note that Ngeow et al. (2017) recently presented an analysis of the Sloan Digital
Sky Survey (SDSS) colors of RR Lyrae stars at maximum and minimum light based on Stripe 82 data. The advantage of our study is that since we have RR Lyrae stars residing in the same cluster, we are able to probe absolute magnitudes and colors at a fixed distance, greatly minimizing distance uncertainties from the equation.

The paper is laid out as follows. The imaging data, processing, and photometry are described in Section 2. A description of the periodic variable stars identified in this work, namely 66 RR Lyrae stars and 1 SX Phe star, are shown in Section 3, and the location of these stars in the color–magnitude diagram (CMD) of M5 is discussed in Section 4. Section 5 presents the average colors at minimum light of both the fundamental-mode (RRab) and first overtone (RRc) RR Lyrae stars in different filters, as well as discussing dependence with period and metallicity. Section 6 provides period–luminosity (P–L) relationships for the RR Lyrae stars in M5 in the DECam ugriz system. Conclusions are provided in Section 7.

2. Data and Photometry

Observations were obtained during 2013 and 2014 with the DECam imager on the 4 m Blanco Telescope at Cerro Tololo Inter-American Observatory (CTIO), Chile. Repeated DECam images of a field centered on M5 (R.A. = 15:18:33.2, decl. = +02:04:51.7, J2000.0) were obtained using the u∗, g, r, i, and z filters. The large field of view (FOV) of DECam (2’’2) easily covers the whole globular cluster with only the central CCDs of the camera (Figure 1). The journal of observations (date—evening—and number of observations per filter) are recorded in Table 1. M5 is a nearby globular cluster located at only 7.5 kpc from the Sun, whose RR Lyrae stars are henceforth expected to be bright, at V magnitudes of ∼15.1 (Harris 1996). Exposure times were therefore short in our images with 30 s in the u band and just 10 s in all the other filters. On photometric nights, observations were also made of photometric standards recently established by Narayan et al. (2016). For RR Lyrae stars, it is best when the targets can be observed several times throughout the night, because periods are less than a day. The observations of M5 were made, however, on assigned nights when fields near the Galactic center were the primary targets. As a result of the large difference in R.A. between M5 and the Galactic bulge fields, M5 could only be observed for part of the night. In addition, many of the observations reported in Table 1 were taken continuously with separations of only minutes. Because periods of RR Lyrae stars range from 0.2 to 0.9 days, that small separation in time does not enable proper sampling of the light curves. This non-optimal cadence has some adverse effects for sampling the light curves, which we discuss later in the paper.

![Figure 1](https://example.com/image1.png)

**Figure 1.** Density map of the 60,335 objects detected in the field of view of DECam centered on M5 in the gri filters. For reference, the black circle marks 10 r1 of the cluster, with r1 = 1.77 (Harris 1996). Colored diamonds show the location of the periodic variable stars identified in this work. All of the red diamonds match known stars in the catalog of variable stars of M5 (Clement et al. 2001). The blue diamonds did not have an entry in that catalog. Because of their distance from the center of the cluster and their faint magnitudes, they should be distant halo stars. The diamonds encircled in blue are two new discoveries.

**Table 1**

| Date       | Nu | Ne | Nr | Ni | Nz |
|------------|----|----|----|----|----|
| 2013 Jun 7 | 2  | 2  | 3  | 2  | 2  |
| 2013 Jun 8 | 8  | 8  | 13 | 8  | 8  |
| 2013 Jun 9 | 11 | 12 | 17 | 13 | 14 |
| 2013 Jun 21| 1  | 3  | 6  | 3  | 4  |
| 2014 Mar 7 | 8  | 8  | 8  | 8  | 8  |
| 2014 Mar 8 | 6  | 6  | 6  | 6  | 6  |
| 2014 Mar 9 | 12 | 12 | 12 | 12 | 12 |
| **TOTAL**  | 50 | 53 | 68 | 54 | 56 |
2. Aperture corrections were calculated independently for each CCD. Unlike for MOSAIC, as a result of the excellent optico-mechanical layout of DECam, and the use of the hexapod for focus and alignment, no variation in aperture corrections as a function of position in the field can be seen within the area covered by an individual CCD. Because the aperture corrections are calculated independently for each CCD, any PSF variations over large changes in field position are effectively accommodated on a CCD-to-CCD granularity.

The instrumental magnitudes were calibrated to the system defined by Narayan et al. (2016) using observations of two of the standard stars from that paper that were observed on photometric nights contemporaneously with the observations presented here. As described in that paper, these magnitudes are defined using spectrophotometric fluxes for the standards, convolved through DECam passbands and typical atmospheric extinction at CTIO, and are therefore native to the DECam instrument, analogous, but not identical to the SDSS system.

Absolute photometry was checked by comparing with the SDSS photometry of M5 provided by An et al. (2008). For this comparison, we transformed our catalog to the SDSS system using equations derived by the Dark Energy Survey Collaboration (D. Tucker 2017, private communication). The offsets between the two sets are 0.05, 0.02, 0.003, 0.03, and 0.02 mag in $ugriz$, respectively.

A total of $16.2 \times 10^8$ individual measurements were processed and stored in a MySQL database. The photometry was cleaned by eliminating measurements if (1) they were within 50 pixels from the borders of the CCDs, (2) there were two or more cosmic rays detected near the object within a radius of the FWHM of the major axis of the fitted PSF, (3) other objects were found within a radius of the FWHM of the major axis of the fitted PSF of the object, and their contribution relative to the object’s flux is $>0.3$ mag, (4) the fitted sky value for an object is $<\text{SKYLOW}$ or $>3\times\text{SKYHI}$, where SKYLOW and SKYHI are the second and ninetieth percentile, respectively, of the distribution of fitted sky values of all objects in the CCD in which the object is found, (5) the DoPHOT reported photometric error is higher than twice the average reported error of all stars for that image that share the same half magnitude bin, and (6) the photometric error of a measurement is significantly higher than the average of the errors of all measurements for the same star. Specifically, we eliminated measurements if the error was $>\langle \text{error} \rangle + 3.5 \sigma_{\text{error}}$, where $\langle \text{error} \rangle$ is the average of the photometric error of all measurements for that star and $\sigma_{\text{error}}$ is the standard deviation of the error distribution. Cosmic rays are identified, and affect pixels masked, by the DoPHOT program as part of the photometry measuring process. The elimination of stars with more than two cosmic rays in its immediate neighborhood from further analysis affects less than 2.4% of the detected stars. We also required that there were at least five good measurements per object in each filter. The final number of objects in our catalogs ranged from 43,792 in the $u$ band to 176,704 objects in the $r$ band.

3. RR Lyrae Stars in M5

RR Lyrae stars were identified in the data by using the procedure described in detail in Saha (2017, in preparation). Here, we summarize the most important details. Variable stars
were flagged using a bootstrap $\chi^2$ using DoPHOT reported photometric errors. A visual tool that blinks between the brightest and faintest image for each star enabled either confirmation or rejection of the variability flag assignment. More than 90% of the flagged cases were visually confirmed. Then, periodic stars were searched using the Psearch algorithm (Saha & Vivas 2017), which combines Fourier transforms and the classical Lafler & Kinman method (a string-length method, Lafler & Kinman 1965) in the five photometric bands simultaneously, which results in a powerful tool for sparse data. The resulting periodogram for each star was visually inspected interactively, allowing for exploration of the different peaks in the diagram. Periodic variable stars were then selected based on the shape of their light curve, period, and amplitude. A total of 66 RR Lyrae stars and 1 SX Phe were recognized in the field of M5. The individual measurements for the periodic variable stars are provided in Table 2 as an electronic table. The table contains ID, MJD, filter, magnitude, and its error. Light curves for all the stars are provided as online only material. Figure 2 shows an example for one of the stars.

The non-optimal cadence of our observations prevented the determination of the correct period for some of the RR Lyrae stars. We took advantage of the fact that the variable stars in M5 have been extensively studied before and adopted in several cases the published periods in the catalog of Clement et al. (2001), which in the case of M5 had an update\(^8\) in 2015 June. A recent revision of variable stars in M5 is also provided as RR Lyrae stars, but the other two, namely 113495 and 139277, have not been cataloged before and should be considered new discoveries.

In Table 3, we present the list of periodic variable stars. It contains ID, R.A., decl., period in days, type of pulsating star, mean magnitudes in $ugriz$, and magnitudes at minimum light ($m_{\text{mag}}$) that were measured as explained in Section 5. The last column provides the cross-identification with the $V^*$ identification in Clement et al. (2001) or the ID in the CRTS. The two new stars are denoted as “NEW.” The reported mean magnitudes in Table 3 are not plain averages but were obtained by integrating the best fitted template of the light curve in intensity units, and transforming back to magnitudes. This method of calculating the mean magnitudes avoids the biases toward minimum magnitudes (because the RR Lyrae stars spend most of their pulsation cycle time at minimum light) as well as those biases that may appear as a result of unevenly sampled light curves.

We estimated the photometric errors in each band by determining the standard deviation of all of the individual magnitudes for each star in each CCD. Because most of the stars in the field are non-variable, the standard deviation provides a good estimate of the real photometric errors. In the CCDs containing the bulk of the M5 stars, which are representative of the crowded environment of our observations, these errors average 0.013, 0.011, 0.011, 0.012, and 0.012 mag at the level of the horizontal branch (HB) in the $u$, $g$, $r$, $i$, and $z$ bands, respectively.

4. Color–Magnitude Diagrams

CMD of stars within 10 $r_h$ ($r_h = 1.77$, Harris 1996) are shown in Figure 3 using different filter combinations. These CMDs were built with the average magnitudes for each star in the catalog. The large area covered by DECam results in very sharp features of the cluster because of the high number of stars included in these diagrams. However notice that, due to the gap between CCDs and our constraint in photometry near the border of the CCDs, there is a strip of 1′.38 centered on the cluster that is not covered in our catalogs (see Figure 1). The catalog associated with these diagrams can be obtained from Table 4. The $\sigma_i$ in this table refers to the standard deviation of the mean of all the measurements for a star in each filter.

The HB is quite horizontal in the $g$ band (Figure 3, left panel), while it has a significant slope in redder bands like the $z$ band shown in the right panel. As expected, all RR Lyrae stars within the radius of 10 $r_h$ lie on top of the HB of the cluster. The obvious outlier below the HB (at $g \sim 16.2$) is an SX Phe star with a period of only 0.0898 days. Neither the SX Phe star nor the RR Lyrae stars outside that radius (Figure 1) will be used in the following analysis.

5. Minimum Light Colors of RR Lyrae Stars in M5

In order to obtain the color at minimum light, we chose to measure the magnitude of the template fitted to each RR Lyrae star at phase $\phi = 0.65$, as shown in Figure 2. Because not all of the light curves in our data are well sampled, the use of the template is particularly useful for cases where the light curve is lacking observations near minimum light and near maximum light, which is needed to define the initial phase ($\phi = 0$). Each star was measured in all available bands and the magnitudes at

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\(^8\) http://www.astro.utoronto.ca/~clement/read.html

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**Table 2**

| ID     | MJD       | Filter | Mag   | Error |
|--------|-----------|--------|-------|-------|
| 16339  | 56451.722332 | $u$    | 18.552 | 0.027 |
| 16339  | 56451.723139 | $u$    | 18.590 | 0.024 |
| 16339  | 56452.499995 | $u$    | 18.703 | 0.028 |
| 16339  | 56452.500658 | $u$    | 18.641 | 0.030 |
| 16339  | 56452.613786 | $u$    | 18.287 | 0.022 |

(This table is available in its entirety in machine-readable form.)
Table 3
Periodic Variable Stars Identified in the M5 Field

| ID  | R.A.  | Decl.  | Period | Type | (u) | (g) | (r) | (i) | (z) | u_ref | g_ref | r_ref | i_ref | z_ref | Other Identification |
|-----|-------|--------|--------|------|-----|-----|-----|-----|-----|-------|-------|-------|-------|-------|---------------------|
| 113495 | 15:15:34.11 | +01:49:30.5 | 0.63013 | ab  | 18.43 | 17.82 | 17.57 | 17.51 | 17.46 | 18.66 | 18.04 | 17.69 | 17.61 | 17.56 | NEW               |
| 114707 | 15:16:49.73 | +02:48:42.9 | 0.65687 | ab  | 18.72 | 18.09 | 17.84 | 17.78 | 17.74 | 19.03 | 18.33 | 18.01 | 17.90 | 17.86 | CRTS_J151649.7+024841 |
| 72475 | 15:17:24.23 | +02:04:24.1 | 0.34908 | c   | 15.19 | 14.74 | 14.65 | 14.69 | 14.67 | 15.58 | 15.11 | 14.88 | 14.89 | 14.83 | V67                |
| 139277 | 15:18:06.77 | +01:18:10.5 | 0.53037 | ab  | 19.93 | 19.35 | 19.21 | 19.21 | 19.16 | 20.51 | 19.73 | 19.45 | 19.39 | 19.35 | NEW               |
| 74636  | 15:18:08.04 | +02:03:45.8 | 0.45141 | ab  | 15.73 | 15.12 | 15.05 | 15.11 | 15.09 | 16.11 | 15.54 | 15.33 | 15.32 | 15.27 | V29                |

(This table is available in its entirety in machine-readable form.)
this phase are recorded in Table 3 as \( m_{\text{ref}} \). In the original work by Sturch (1966), the minimum color is defined as the mean color between phases 0.5 and 0.80. We experimented with this definition as well but found no significant difference with our values and decided to keep the single-phase definition. A similar conclusion was also reached by Kunder et al. (2010).

We computed mean observed colors at minimum light of the 47 M5 RR\( ab \) in the DECam passband system and recorded the results in Table 5. For comparison, we also provide in Table 5 the mean colors (the colors calculated with the mean magnitude in each band) and their standard deviations. The dispersion observed in the colors at minimum light are always lower than the ones from the mean colors, confirming that the former is the one suitable to be used as a color standard.

As expected from the early works of Sturch (1966) in the \( UBV \) bands and later works by Mateo et al. (1995), Guldenschuh et al. (2005) and Kunder et al. (2010) in \( VRI \), the colors at minimum light of the fundamental-mode RR

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### Table 4

| ID   | R.A. (deg) | Decl. (deg) | \( u \) | \( \sigma_u \) | \( g \) | \( \sigma_g \) | \( r \) | \( \sigma_r \) | \( i \) | \( \sigma_i \) | \( z \) | \( \sigma_z \) |
|------|------------|-------------|--------|---------------|--------|---------------|--------|---------------|--------|---------------|--------|---------------|
| 18709| 229.46147  | 2.29986     | 16.438 | 0.006         | 15.264 | 0.005         | 14.692 | 0.005         | 14.532 | 0.006         | 14.452 | 0.003         |
| 18711| 229.48143  | 2.28796     | 16.792 | 0.005         | 15.478 | 0.006         | 14.781 | 0.005         | 14.552 | 0.007         | 14.425 | 0.003         |
| 18712| 229.48684  | 2.30266     | 16.082 | 0.005         | 14.999 | 0.004         | 14.531 | 0.005         | 14.431 | 0.008         | 14.395 | 0.004         |
| 18713| 229.49202  | 2.28002     | 15.141 | 0.007         | 13.882 | 0.004         | 13.334 | 0.007         | 13.204 | 0.012         | 13.139 | 0.003         |
| 18714| 229.60225  | 2.23137     | 16.374 | 0.011         | 15.347 | 0.015         | 14.874 | 0.011         | 14.768 | 0.006         | 14.732 | 0.010         |

(This table is available in its entirety in machine-readable form.)

### Table 5

Mean and Minimum Light Colors of Fundamental-mode RR Lyrae Stars in M5

| Color | \( (X - Y)^a \) | Std Dev\(^b\) | \( (X - Y)_{\text{min}}^c \) | Std Dev\(^d\) | \( (X_0 - Y_0)_{\text{min}}^e \) |
|-------|----------------|-------------|-----------------------------|-------------|-----------------------------|
| \( u - g \) | 0.575         | 0.059       | 0.644                       | 0.034       | 0.616 ± 0.031                |
| \( g - r \) | 0.157         | 0.055       | 0.288                       | 0.035       | 0.251 ± 0.025                |
| \( g - i \) | 0.147         | 0.076       | 0.331                       | 0.041       | 0.274 ± 0.024                |
| \( r - i \) | -0.010        | 0.023       | 0.043                       | 0.017       | 0.022 ± 0.021                |
| \( r - z \) | 0.016         | 0.029       | 0.082                       | 0.023       | 0.049 ± 0.020                |
| \( i - z \) | 0.026         | 0.011       | 0.039                       | 0.016       | 0.026 ± 0.020                |

Notes.

\(^a\) Average of the observed mean colors.
\(^b\) Standard deviation of the distribution of the observed mean colors.
\(^c\) Average of the observed colors at minimum light.
\(^d\) Standard deviation of the distribution of observed colors at minimum light.
\(^e\) Average of the reddening-corrected colors at minimum light and its error.
Lyrae stars have only a very small dispersion. The dispersion is particularly low in the infrared colors because they are freer of line blanketing. In particular, the \((r-i)_{\text{min}}\) and \((i-z)_{\text{min}}\) colors have dispersions of \(\lesssim0.02\) mag, which are about the same size as the observed photometric errors in the colors at the level of the HB of M5.

Assuming a reddening of \(E(B-V) = 0.035 \pm 0.005\) for M5 (Carretta et al. 2000), a standard reddening law of \(R_V = 3.1\) and the following extinction to reddening \((A_i/E(B-V))\) values\(^9\) for \(ugriz\), 3.995, 3.214, 2.165, 1.592, and 1.211 (Schlafly & Finkbeiner 2011), we transformed those mean observed colors at minimum light to dereddened values (see Table 5). The errors quoted in the dereddened colors at minimum light include both the observational errors at the level of the HB in each band and the error in the assumed extinction toward the cluster.

5.1. Dependence of Colors at Minimum Light with Periods

A dependence on period may be responsible for part of the dispersion observed in some of the colors at minimum light discussed above. We checked for such dependence and present the results in Figure 4, this time including the RRc as well. Similar behavior as that observed in Figure 4 is seen in the analysis of SDSS colors by Ngeow et al. (2017). Although, for the colors from redder filters, the dependence on periods seems to be small, for \((u-g)_{\text{min}}, (g-r)_{\text{min}}, \) and \((g-i)_{\text{min}}\), it is large enough that appropriate corrections are needed to obtain the true color at minimum light for an RR Lyrae star of a given period. We fit parabolic functions to the RRab data in each color \((X-Y)_{\text{min}}\) as a function of the logarithm of the period \((P)\) of the form

\[
(X-Y)_{\text{min}} = a + b \log P + c \log^2 P
\]  

(1)

The coefficients of such fits and their rms are shown in Table 6, and plotted as solid red lines in Figure 4. The standard deviation values and the rms of the fits in Tables 5 and 6 suggests that better results can be obtained when using colors from redder DECam filters to estimate interstellar extinction toward RR Lyrae stars as the rms of the fitted functions are the smallest in these bands. When taking into account the period, the use of period-corrected minimum colors may lead to errors in the true color of \(\lesssim0.016\) mag in \((r-i)_{\text{min}}, (r-z)_{\text{min}}\), and \((i-z)_{\text{min}}\). The coefficients in Table 6 can then be used to obtain the intrinsic colors of RRab of a given period and, thus, to determine accurate line-of-sight reddening toward those stars.

Two RRab were left out from these fits because they showed discrepant behaviors (see Figure 4): 74799 and 74542. Our data for the former is consistent with a sinusoidal light curve and small amplitude. The colors for this star are too red to be an RRc. Arellano Ferro et al. (2016) flagged this star (V85 in their nomenclature) as a Blazhko star, but their light curve looks clearly like an RRab. Thus, it may be a case of extreme Blazhko effect or mode changing. On the other hand, star 74542 has very few points in the \(g\) and \(r\) light curves (<10) and that may have produced discrepant colors.

In the past, Kanbur & Fernando (2005) and Kunder & Chaboyer (2008) reached the conclusion that no strong dependence on period existed for RR Lyrae stars measured in the \((V-R)\) color. This is still almost true (very small dependence) in colors combining the \(riz\) DECam filters, but the dependence is important in colors that include the \(u\) or \(g\) filters. We note that our photometry is more precise than the MACHO photometry used in Kanbur & Fernando (2005), and our sample size is larger (more than twice as large) as that in Kunder & Chaboyer (2008), which likely contributes to the reason we are able to see this small trend.

We also explored the behavior of the color at minimum light of RRc in M5, measured at the phase corresponding to the lowest point of their light curves. For these stars, we used the fundamentalized period, \(P_f\), as defined in Catelan (2009):

\[
\log P_f = \log P + 0.128.
\]  

(2)

The RRc are plotted with blue symbols in Figure 4. Given the observed behavior of these stars in the plots and because there are only 14 RRc in our data, we decided to fit only linear relationships. In the figure, it can be seen that there are some discrepant points in most of the panels that were left out from the fit. They corresponded to stars 74561, 72475, and 74395. RRc stars are hard to separate unambiguously from contact binaries and contamination by those stars may be causing some of the observed discrepancies. The results of the linear fits are shown as blue dashed lines in Figure 4 and the slope, intercept, and rms are reported in Table 7.

From Figure 4 it is clear that RRc do not follow well the trend observed for the RRab. A small offset in the colors is observed between the two types of RR Lyrae stars and, thus, it is more convenient to use separate relationships for each type. As in the case of RRab, the smallest dispersions in the Color–\(\log P_f\) relationships for RRc were also obtained when using colors constructed with the redder filters \(r, i,\) and \(z\).

Notice that the coefficients given in Tables 6 and 7 provide the colors at minimum light of the RR Lyrae stars in M5. If they are to be used for stars in any other part of the sky, they should be corrected for reddening first. For convenience, we provide, in the last column of Table 6, the excess colors for the different DECam colors assuming an \(E(B-V) = 0.035\) for M5 (Carretta et al. 2000) and the reddening law and coefficients given above.

5.2. Dependence on Metallicity

We also need to understand the dependence of the color at minimum light on metallicity. Sturch (1966) reported a non-negligible dependence of \(B-V\) with metallicity, with \(U-B\) showing a much larger dependence. He was thus able to mitigate the effect on \(B-V\) by referring to \(U-B\). This suggests that the metallicity dependence arises either wholly, or mostly, due to line blanketing. If so, by using redder colors, where the line blanketing is much smaller, we expect to further mitigate the effect. To get a quantitative estimate, compare Table 8 in Jones et al. (1987a) with Table 4 in Jones et al. (1987b). In the former, synthetic colors are calculated for various temperatures and gravities for \([\text{Fe}/\text{H}] = -2.2\) and in the latter, the same for \([\text{Fe}/\text{H}] = -0.75\). We see that the predicted \(B-V\) colors at the same temperature and gravity differ by as much as 0.06 mag for temperatures in the range 5500 and 6500 K, while corresponding \(V-K\) colors differ by only 0.02 mag. Furthermore, Figure 2 in Blanco (1992b), in which the systematics and accuracy of Sturch’s original relations are

\(^9\) These coefficients slightly differ from those in Schlafly & Finkbeiner (2011) since they are calculated using updated values for the effective DECam throughput (E. Schlafly 2017, private communication).
re-examined) indicates that the metallicity corrections for $B - V$ are independent of the temperature, in the range of 5500–6500 K.

Figure 4. Dependence of the colors at minimum light of the RR Lyrae stars in M5 with the logarithm of the fundamentalized period $P_f$. Red symbols correspond to RRab, while blue symbols are the RRc. The red solid line is a fit of the RRab data, while the blue dashed line is a linear fit to the RRc stars.

Table 6
Coefficients and rms of the Parabolic Fits to the Log ($P_f$)–Color at Minimum Light Relationship for RRab

| Color | $a$   | $b$   | rms  | $E(X - Y)$  |
|-------|-------|-------|------|-------------|
| $u - g$ | 0.692 | -0.669 | 0.029 | 0.027       |
| $g - r$ | 0.343 | -0.753 | 0.022 | 0.037       |
| $g - i$ | 0.404 | -0.973 | 0.026 | 0.057       |
| $r - i$ | 0.060 | -0.220 | 0.012 | 0.020       |
| $i - z$ | 0.047 | -0.102 | 0.016 | 0.033       |
| $r - z$ | 0.108 | -0.322 | 0.016 | 0.013       |

Table 7
Coefficients and rms of the Linear Fits to the Log($P_f$)–Color at Minimum Light Relationship for RRc

| Color | Intercept | Slope | rms  |
|-------|-----------|-------|------|
| $u - g$ | 0.730 | 0.453 | 0.026 |
| $g - r$ | 0.589 | 1.165 | 0.023 |
| $g - i$ | 0.654 | 1.381 | 0.023 |
| $r - i$ | 0.069 | 0.226 | 0.017 |
| $i - z$ | 0.126 | 0.306 | 0.014 |
| $r - z$ | 0.131 | 0.376 | 0.015 |

Note.

$^a$Excess color corresponding to $E(B - V) = 0.035$ (Carretta et al. 2000) using the extinction to reddening coefficients given in Section 5.

With this preface, to explore the metallicity dependence of colors from DECam at minimum light, we used the flux from a Kurucz model$^{10}$ with $T_{\text{eff}} = 6250$ K, log $g = 2.0$, and three

$^{10}$ As presented in ftp://ftp.stsci.edu/cdbs/grid/k93models.
different metallicities: $[\text{Fe/H}] = -1.0, -2.0, +0.5$. We convolved these spectra with the DECam filter throughput curves\(^{11}\) and calculated the color of the synthetic RR Lyrae star at each metallicity (Figure 5). The chosen temperature and gravity are representative of a fundamental RR Lyrae star near minimum light (in unpublished work, A. Saha has ascertained that this choice is consistent with both the SED including the Balmer jump, as well as the Balmer line profiles for six bright RR Lyrae stars spanning 2 dex in metallicity, U Lep, RX Eri, ST Oph, U Pic, SV Eri, and HH Pup, while in their low-light phases). In any case, as Figure 2 in Blanco (1992a) indicates, the exact choice of temperature should not significantly alter the derived dependencies.

The results of these calculations indicate that the colors $(r - i)$, $(r - z)$, and $(i - z)$ may have maximum variations of 0.027, 0.042, and 0.015 mag, respectively, in the full metallicity range explored. These differences are even smaller in the range of metallicity from $-2 < [\text{Fe/H}] < -1$, where the differences in color amount to only 0.006, 0.010, and 0.004 in $(r - i)$, $(r - z)$, and $(i - z)$, respectively.

The variations of the $(u - g)$ color with metallicity are large enough to make it not suitable for use as a standard color measurement if the metallicity of the RR Lyrae star is not known. These large variations have been observed before, in the $UBV$ system by Sturch (1966) and others. This is expected because metallicity expresses itself through line-blanketing and opacity effects in the blue ($u$ and $g$) and ultra-violet, but much less so as one goes progressively to the red. Colors involving the $g$ filter ($g - r$ and $g - i$) have variations of colors in the range of metallicity studied as large as 0.1 mag.

### 6. Absolute Magnitudes of M5 RR Lyrae Stars in DECam Filters

Calibration of the absolute magnitudes of RR Lyrae stars in the DECam filters does not exist to date. For SDSS passbands, $P-L$ relationships have been provided by Cáceres & Catelan (2008) that are based on theoretical models. Here we determine the empirical values of the absolute magnitudes of the RR Lyrae stars in M5 in the DECam natural filter system in which our data have been calibrated. In Figure 6, we show the observed mean magnitude of the RR Lyrae stars as a function of the logarithm of their pulsation period. As before, the period for the $RR_c$ stars has been “fundamentalized” using Equation (2). For all of the filters, the $RR_c$ stars seem to be slightly brighter and thus we fit $P-L$ relationships separately for each type. The best linear fits are given in Table 8. The dependence of absolute magnitude with periods in $r$, $i$, and $z$ is strong but very well constrained, as implied by the low rms values of the linear fits. In the $u$ and $g$ bands the correlation between mean magnitude and period is less obvious and the resulting fit has larger residuals. In any case, the slopes of the relationships in these filters seem to be small, which is a consequence of the HB being mostly horizontal in these bands (see, for example, the CMD in Figure 3). The $RR_ab$ stars have tighter relationships than the $RR_c$ stars.

Layden et al. (2005) determined the true distance modulus of M5 using main-sequence fitting and obtained $(m - M)_0 = 14.45 \pm 0.11$ mag, a value that is consistent with 14.44 \pm 0.02

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\(^{11}\)\url{http://www.ctio.noao.edu/noao/content/Dark-Energy-Camera-DECam}
given by Coppola et al. (2011) based on IR observations of RR Lyrae stars. Assuming the latter and an excess color $E(B-V) = 0.035 \pm 0.005$ (Carretta et al. 2000), we scaled the intercept parameters in Table 8 to obtain the following absolute P–L relationships. The error in the distance modulus and interstellar extinction have been added in quadrature to the intercept term.

\[
M_u (ab) = (-0.10 \pm 0.24) \log P + (1.10 \pm 0.13) \\
M_u (c) = (-0.38 \pm 0.36) \log P + (0.88 \pm 0.18) \\
M_g (ab) = (-0.57 \pm 0.17) \log P + (0.43 \pm 0.12) \\
M_g (c) = (-0.72 \pm 0.32) \log P + (0.27 \pm 0.16) \\
M_r (ab) = (-1.28 \pm 0.11) \log P + (0.12 \pm 0.11) \\
M_r (c) = (-1.35 \pm 0.21) \log P + (0.01 \pm 0.13) \\
M_i (ab) = (-1.59 \pm 0.09) \log P + (0.07 \pm 0.11) \\
M_i (c) = (-1.61 \pm 0.16) \log P + (0.00 \pm 0.12) \\
M_z (ab) = (-1.68 \pm 0.08) \log P + (0.03 \pm 0.11) \\
M_z (c) = (-1.73 \pm 0.14) \log P - (0.04 \pm 0.12).
\]
Notice that although it is expected that absolute magnitudes also have a dependence on the metallicity, we are dealing here with RR Lyrae stars within a single globular cluster with a very small metallicity dispersion. The metallicity of M5 is [Fe/H] = −1.25 ± 0.05 (Dias et al. 2016).

For comparison, we calculated the predicted values of the absolute magnitude in $i$ and $z$ for a RR Lyrae star with $P = 0.5$ day, using the relationships given for the SDSS system by Cáceres & Catelan (2008) that are based on synthetic spectra of RR Lyrae stars. To do this, we assumed [Fe/H] = −1.25 and $[\alpha/Fe] = 0.24$ (Dias et al. 2016). Once the resulting values are transformed to the DECam system, the discrepancy between empirical absolute magnitudes and the ones derived from the equations in Cáceres & Catelan (2008) are only 0.02 and 0.03 mag in $i$ and $z$ respectively. We notice that Cáceres & Catelan (2008) were unable to produce relationships for $M_r$, $M_v$, and $M_B$ because they were not tight enough.

7. Conclusions

In this paper, we provide colors at minimum light and absolute magnitudes of RR Lyrae stars (both RRab and RRc) in the ugriz DECam system based on observations of the Galactic globular cluster M5. The colors at minimum light of RR Lyrae stars constitute an important tool to determine the reddening along the line of sight up to the distance of the star. This is our main motivation for the present study because these calibrations will be applied to a large-scale survey of RR Lyrae stars in the Bulge in forthcoming papers.

We studied the behavior of different DECam colors at minimum light with period and conclude that the reddest colors, $(r-i)_{\text{min}}$, $(r-z)_{\text{min}}$, and $(i-z)_{\text{min}}$, are the best options to be used as color standards. The dependence of color at minimum light with period is well behaved and we were able to fit functions to both RRab and RRc stars with resulting rms values $<0.02$ mag.

A caveat of this work, however, is the use of a single cluster with a fixed metallicity ([Fe/H] = −1.25). We tested to some extent the possible dependence on metallicity by analyzing synthetic spectra in the range of $-2.0 < [\text{Fe/H}] < +0.5$ and conclude that the color variations are at most 0.02, 0.03, and 0.01 mag in that range of metallicity for $(r-i)_{\text{min}}$, $(r-z)_{\text{min}}$, and $(i-z)_{\text{min}}$, respectively. Also, from previous works based on VRI magnitudes (Guldenschuh et al. 2005; Kunder et al. 2010), we do not expect a strong dependence of colors at minimum light with metallicity. It will be desirable, however, to study other globular clusters with a range of metal content in order to confirm this statement. On the other hand, our main motivation for this work is to apply these calibrations to RR Lyrae stars in the Galactic Bulge, which is in a metallicity regime not very different to that of M5 (for example, Walker 1990).

We also provide an empirical calibration of the absolute magnitude of the M5 RR Lyrae stars in the DECam system. Again, the reddest filters, $riz$ are the best options for obtaining a good absolute magnitude (and hence, distance) since they produce tight P-L relationships for the RRab stars, with dispersion amounting to 0.03, 0.02, and 0.02 mag in $r$, $i$, and $z$, respectively. The dispersions obtained for the RRc in those bands are also small, <0.1 mag.

With its large FOV, DECam is an excellent instrument to study RR Lyrae stars over large extensions in the sky. We anticipate that the calibrations provided in this paper will be useful for different projects that use this type of variable as standards for distance and color.

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Facility: Blanco (DECam).

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