THE PERIOD-LUMINOSITY RELATION OF RR LYRAE STARS IN THE SDSS PHOTOMETRIC SYSTEM

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ABSTRACT

We provide the first detailed study of the RR Lyrae period-luminosity (PL) relation in the ugriz bandpasses of the Sloan Digital Sky Survey (SDSS) filter system. We argue that tight, simple PL relations are not present in the SDSS filters, except for the redder bandpasses i and (especially) z. However, for all bandpasses, we show that by incorporating terms involving a (fairly reddening-independent) “pseudocolor” $C_0 \equiv (u - g)_0 - (g - r)_0$, we can obtain tight (nonlinear) relations. We provide such theoretically calibrated relations in the present paper, which should be useful in deriving precise absolute magnitudes (hence distances) and intrinsic colors (hence reddening values) even to individual field RR Lyrae stars. For applications to cases in which photometry in all five passbands may not be available, we also provide simple (although less precise) average PL relations for the i and z bandpasses, which read as

$$M_i = 0.839 - 1.295 \log P + 0.211 \log Z$$

and

$$M_z = 0.908 - 1.035 \log P + 0.220 \log Z.$$

Similarly, simple period-color relations for $(r - i)_0$, $(g - r)_0$, and $(u - z)_0$ are also provided.

Subject headings: distance scale — stars: distances — stars: horizontal-branch — stars: variables: other

1. INTRODUCTION

The Sloan Digital Sky Survey (SDSS) has given the scientific community an unprecedented chance to systematically map a large area of the sky, using its own special five-band filter system. In the process, an overwhelming amount of data has been amassed, which can be used to perform many different types of scientific studies. Of particular interest to us is the fact that the SDSS has also provided, with unprecedented detail, a map of the spatial distribution of different stellar populations across the Galaxy, which is increasingly being used to trace new structures in the Galactic halo (e.g., Belokurov et al. 2007), some of which may plausibly be related to the hundreds of elusive “protogalactic fragments” that are predicted, in the ΛCDM cosmological paradigm, to have given birth to a galaxy like the Milky Way (e.g., Abadi et al. 2003). In this sense, RR Lyrae stars have proven to be a stellar component that is consistently present in most, and possibly all, of these structures (e.g., Greco et al. 2008; Kuehn et al. 2008). Light curves for many variable stars in the SDSS filter system have been provided by the SDSS II Survey, a year extension of the original SDSS survey, with images of the same fields taken every other night, with the main goal to detect supernova explosions. However, it remains at present difficult to obtain reliable distances from them, since so far no detailed study of the properties of RR Lyrae stars in the SDSS system has been performed, with the notable exception of Marconi et al. (2006). In the same vein, it is still not possible at present to directly extract reliable distance information from detailed RR Lyrae light curves obtained in the SDSS system, as are now becoming increasingly common (e.g., De Lee et al. 2007; Sesar et al. 2007; Wilhelm et al. 2008).

Accordingly, the purpose of the present study is to provide the first systematic investigation of the RR Lyrae period-luminosity (PL) relation in the bandpasses of the SDSS system, which should enable the determination of more reliable distances to individual RR Lyrae stars for which data in the SDSS system are available than has been possible thus far. This paper presents an extension of the work by Catelan et al. (2004), who obtained such a PL relation for the UBVRIJHK passbands of the Johnson-Cousins-Glass photometric system, and by Cortés & Catelan (2008), who studied the PL relations in the Strömgren system. Its structure is quite similar to that in Catelan et al. and Cortés & Catelan. We begin by presenting, in § 2, the theoretical framework on which our study is based. In § 3, we explain the origin of the derived PL relations, whose calibrations are provided in § 4. Some final remarks are provided in § 5.

2. MODELS

In order to derive the PL relations, we computed a series of horizontal branch (HB) simulations, following recipes similar to those presented in Catelan et al. (2004) and Cortés & Catelan (2008). We used the evolutionary tracks given by Sweigart & Catelan (1998) and Catelan et al. (1998) for $Z = 0.0005$, 0.001, 0.002, and 0.006. The main-sequence helium abundance by mass is assumed to be $Y = 0.23$, and solar-scaled compositions are adopted. Catelan et al. argue that these models are consistent with a distance modulus to the Large Magellanic Cloud of $(m - M)_0 = 18.47$ mag. Note, however, that this value is based on the empirical prescriptions for the LMC by Gratton et al. (2004); using the independent measurements by Borissova et al. (2004), a distance modulus of $(m - M)_0 = 18.50$ mag would be derived instead.

The mass distribution is assumed to be a normal deviate, with a mass dispersion of $\sigma_M = 0.02 \, M_\odot$. In order to pass from the theoretical $(\log L, \log T_{\text{eff}})$ plane to the empirical ones in which the magnitudes in the SDSS photometric system $(u, g, r, i, \text{and } z)$ are used, we have incorporated the bolometric corrections from Girardi et al. (2004) to the code, over the relevant ranges of...
temperature and gravity. The blue edge of the instability strip is computed as prescribed by Caputo et al. (1987), but with a shift of ~200 K applied to the resulting temperatures to provide better agreement with recent prescriptions (Catelan 2004). The instability strip width is taken as $\Delta \log T_{\text{eff}} = 0.075$, which gives us the temperature of the red edge of the instability strip once the blue edge position has been found. When a star lies between the blue and red edges, its period is calculated based on equation (4) of Caputo et al. (1998). Therefore, our relations are directly applicable to fundamental-mode (i.e., RRab or RRc) stars, but the observed periods of first-overtone (RRc or RR1) stars must first be "fundamentalized" according to the relation $\log P_f = \log P_\text{e} + 0.128$ (Catelan 2005 and references therein) before comparing with our results.

In this paper we are interested in finding PL relations for RR Lyrae stars in the SDSS system. To properly take into account the impact of variations in HB morphology, for each of the four studied metallicities, we computed extensive series of HB simulations, including HB types that range from very red to very blue. This leads to a total of 423,766 synthetic RR Lyrae stars that cover a wide range in metallicity and HB types. These stars are then used to search for possible PL relations, as described in the sections that follow.

3. GENESIS OF THE PL RELATIONS IN THE SDSS SYSTEM

As discussed in Catelan et al. (2004), the expected PL relation must be tighter toward the redder passbands (especially in the near-infrared), compared to the visual bands. The effects of temperature and luminosity on the periods affect strongly the shape of the resulting PL relation. In order to better appreciate this, recall that from the period-mean density relation or Ritter’s relation (e.g., van Albada & Baker 1971), periods increase strongly with both an increase in luminosity and a decrease in temperature. While the luminosities of RR Lyrae stars are remarkably uniform for a given metallicity and HB type, the introduction of filters, with their often strongly temperature-dependent bolometric corrections, may add strong slopes to the otherwise “horizontal” branch. Thus, in $u$ and $g$, the cooler stars appear fainter than the bluer ones; conversely, in the redder passbands ($r$, $i$, and $z$), the cooler stars are the ones that appear brighter. Since the cooler/more luminous stars are the ones with longer periods, the end result is that the PL relation will appear increasingly tighter toward the redder passbands, the inverse happening toward the bluer passbands (see Catelan et al. 2004 for a detailed discussion).

This behavior is confirmed in Figure 1 (top), where we show the changes in the absolute magnitude-log-period space, for HB simulations computed for a rather even HB morphology, a metallicity of $Z = 0.002$, and each of the $ugriz$ SDSS passbands. Qualitatively similar results are obtained for other metallicity values and HB morphologies as well. As can be clearly seen, it is only when the redder bandpasses of the SDSS system, namely, $i$ and $z$, are used that one begins to find relatively tight, simple PL relations. This behavior is in total agreement with the previous results by Catelan et al. (2004), who had similarly found that, in the case of the Johnson-Cousins-Glass system, such simple PL relations are present only for $I$ and redder bandpasses.

4. THE RR LYRAE PL RELATION IN THE SDSS SYSTEM CALIBRATED

4.1. Relations Involving a "Pseudocolor"

As shown in Cortés & Catelan (2008), the originally very poor PL relations in the Strömgren (1963) filter system become exceedingly tight when (fairly reddening-independent) Strömgren "pseudocolor" $C_0 \equiv (u-v)_0 - (v-b)_0$ terms are incorporated into these relations. Can something similar be accomplished, in the case of the SDSS system?

To answer this question, we have searched for a combination of blue and red SDSS colors that might also prove relatively reddening-free. We used the extinctions provided online by D. Schlegel,\footnote{See http://astro.berkeley.edu/~marc/dust/data/filter.txt.} according to which one has $E(u)/E(B-V) = 5.16$, $E(g)/E(B-V) = 3.79$, $E(r)/E(B-V) = 2.75$, $E(i)/E(B-V) = 2.09$, and $E(z)/E(B-V) = 1.48$. On this basis, we find that a "pseudocolor" defined as

$$C_0 = (u-g)_0 - (g-r)_0$$

Fig. 1.—Top: RR Lyrae PL relations for the different indicated SDSS filters. Bottom: Corresponding RR Lyrae distributions in the absolute magnitude-log-period–"pseudocolor" plane. Note the dramatic reduction in scatter that is brought about with the inclusion of a $C_0$-dependent term (the correlation coefficient $r$ is shown in the bottom panels). All plots show 650 randomly chosen synthetic RR Lyrae stars from an HB simulation with $Z = 0.002$ and an intermediate HB type.
turns out to be fairly reddening-insensitive, with the unreddened \( C_0 \) and reddened \( C_1 \) quantities being related by the equation

\[
C_0 = C_1 - 0.32(B - V). \tag{2}
\]

That by incorporating such \( C_0 \)-dependent terms can indeed lead to much tighter PL-pseudocolor (PLpsC) relations is confirmed by Figure 1 (bottom), which shows the enormous improvement over the situation in which no such terms are included (Fig. 1, top).

In the course of our research we noticed that tight period-color-pseudocolor (PCpsC) relations are obtained when one includes such \( C_0 \)-dependent terms. This is clearly shown in Figure 2.\(^2\) As a matter of fact, such relations are even tighter than the corresponding PLpsC ones. Therefore, in what follows, we directly provide our theoretically calibrated PLpsC relation in a single bandpass, namely \( z \) (which provides us with the highest correlation coefficient of all the SDSS filters), electing to provide PCpsC relations involving the remainder of the SDSS filters, due to their higher correlation coefficients. From the provided PLpsC relation in \( z \) and the PCpsC relations, one can derive PLpsC relations in a straightforward manner for all other individual SDSS bandpasses.

The final relations that we obtained are thus of the form

\[
mag \text{ or color} = \sum_{i=1}^{2} a_i (\log Z)' + \sum_{i=0}^{2} b_i (\log Z)'(\ln C_0) + \sum_{i=0}^{2} c_i (\log Z)'(\ln C_0)^2 + \sum_{i=0}^{2} d_i (\log Z)'(\ln C_0)^3 + \sum_{i=1}^{3} e_i (\log Z)'(\log P), \tag{3}
\]

where \( \text{mag} \) stands for the absolute magnitude in \( z \), whereas color represents any of the colors \( (u - g)_0 \), \( (g - r)_0 \), \( (r - i)_0 \), or \( (i - z)_0 \). In this expression, \( C_0 \) is the SDSS system’s pseudocolor (eq. [1]), and \( P \) is the fundamentalized RR Lyrae period (in days). The corresponding coefficients, along with their errors, are given in Table 1. (Naturally, the \( c_0 \) coefficient that appears in this table is not the same as the pseudocolor \( C_0 \), which is given in capital letters throughout this paper to avoid confusion.)

We stress that these equations are able to reproduce the input values (from the HB simulations) with high precision. This is shown in Table 2, where the correlation coefficient \( r \) and the standard error of the estimate are given for each of the four equations. We also show, in Figures 3, 4, 5, 6, and 7, the residuals (in the sense eq. [3] minus input values [from the simulations]) for a random subset of 6000 synthetic stars drawn from the original pool of 423,766 synthetic RR Lyrae stars in the HB simulations, for the fits computed for \( z \), \( (u - g)_0 \), \( (g - r)_0 \), \( (r - i)_0 \), and \( (i - z)_0 \), respectively. These plots further illustrate that the SDSS magnitudes and colors can be predicted from the data provided in equation (3) and Table 1 with a precision that is generally at the level of 0.01 mag (or better, especially at low metallicities).

Finally, we note that equation (3) can be trivially expressed in terms of \([\text{Fe}/\text{H}]\); this can be accomplished using the relation

\[
\log Z = [\text{M}/\text{H}] - 1.765, \tag{4}
\]

which is the same as equation (9) in Catelan et al. (2004). In this sense, the effects of an enhancement in \( \alpha \)-capture elements with respect to a solar-scaled mixture, such as observed among Galactic halo stars (e.g., Pritzl et al. 2005 and references therein), can be taken into account by using the following scaling relation (Salaris et al. 1993):

\[
[\text{M}/\text{H}] = [\text{Fe}/\text{H}] + \log (0.638 f + 0.362), \tag{5}
\]

where \( f = 10^{\alpha/\text{Fe}} \). However, such a relation should be used with due care for metallicities \( Z > 0.003 \) (VandenBerg et al. 2000).

4.2. The Effect of the Helium Abundance

The dependence of the RR Lyrae PLpsC relation in the SDSS system on the adopted width of the mass distribution, as well as

\[\text{(Fig. 1, top)}.\]
on the helium abundance, has been analyzed by computing additional sets of synthetic HB’s for $\sigma_M = 0.030 \, M_\odot$ ($Z = 0.001$) and for a main-sequence helium abundance of 28% ($Z = 0.002$). The effect of $\sigma_M$ variations was found to be negligible (see also Catelan et al. 2004 and Cortés & Catelan 2008 for similar results). Therefore, if a correction to the zero point of $M_z$ for $\sigma_M = 0.044/(0.29 \text{ mag at their faintest to } -0.29 \text{ mag at their brightest}), in the $Y_{MS} = 0.23$ case. Therefore, if a correction to the zero point $a_0$ for $M_z$ in Table 1 (and also in eq. [6] below) by $dM_z/dY = -0.044/(0.28 - 0.23) = -0.88$ (i.e., in the sense that eq. [3] predicts too faint magnitudes) is duly taken into account, equation (3) (and similarly eq. [6] below) can also be used to provide useful information on

| Coefficient | Value | Error |
|-------------|-------|-------|
| $a_0$       | 1.3706| 0.0083|
| $a_1$       | 0.8941| 0.0061|
| $a_2$       | 0.1315| 0.0011|
| $b_0$       | -2.6907| 0.0372|
| $b_1$       | -0.8192| 0.0272|
| $b_2$       | -0.0664| 0.0049|
| $c_0$       | 47.9836| 0.3659|
| $c_1$       | 31.7879| 0.2676|
| $c_2$       | 5.2221| 0.0480|
| $d_0$       | 141.7704| 1.2837|
| $d_1$       | 100.6676| 0.8919|
| $d_2$       | 17.4277| 0.1541|
| $e_0$       | 0.3286| 0.0254|
| $e_1$       | 2.0377| 0.0186|
| $e_2$       | 0.3882| 0.0034|

| Coefficient | Value | Error |
|-------------|-------|-------|
| $a_0$       | 1.1983| 0.0030|
| $a_1$       | 0.6282| 0.0022|
| $a_2$       | 0.0939| 0.0004|
| $b_0$       | -2.3672| 0.0133|
| $b_1$       | -1.0552| 0.0097|
| $b_2$       | -0.1536| 0.0018|
| $c_0$       | 36.3361| 0.1311|
| $c_1$       | 24.1760| 0.0959|
| $c_2$       | 3.9668| 0.0172|
| $d_0$       | 113.8830| 0.4599|
| $d_1$       | 80.9365| 0.3195|
| $d_2$       | 13.9681| 0.0552|
| $e_0$       | 1.8627| 0.0091|
| $e_1$       | 1.1097| 0.0067|
| $e_2$       | 0.1792| 0.0012|

| Coefficient | Value | Error |
|-------------|-------|-------|
| $a_0$       | 0.2050| 0.0007|
| $a_1$       | 0.1497| 0.0005|
| $a_2$       | 0.0242| 0.0060|
| $b_0$       | -0.7589| 0.0033|
| $b_1$       | -0.3685| 0.0024|
| $b_2$       | -0.0559| 0.0004|
| $c_0$       | 8.7812| 0.0320|

| Coefficient | Value | Error |
|-------------|-------|-------|
| $a_0$       | 2.1983| 0.0030|
| $a_1$       | 0.6282| 0.0022|
| $a_2$       | 0.0939| 0.0004|
| $b_0$       | -1.3677| 0.0133|
| $b_1$       | -1.0556| 0.0097|
| $b_2$       | -0.1537| 0.0018|
| $c_0$       | 36.3870| 0.1311|
| $c_1$       | 24.1751| 0.0959|
| $c_2$       | 3.9662| 0.0172|
| $d_0$       | 114.0780| 0.4599|
| $d_1$       | 80.9562| 0.3195|
| $d_2$       | 13.9697| 0.0552|
| $e_0$       | 1.8627| 0.0091|
| $e_1$       | 1.1097| 0.0067|
| $e_2$       | 0.1791| 0.0012|

| Coefficient | Value | Error |
|-------------|-------|-------|
| $a_0$       | 0.3218| 0.0011|
| $a_1$       | 0.1907| 0.0008|
| $a_2$       | 0.0290| 0.0001|
| $b_0$       | -0.8054| 0.0049|
| $b_1$       | -0.2516| 0.0036|
| $b_2$       | -0.0313| 0.0006|
| $c_0$       | 15.8088| 0.0487|
| $c_1$       | 10.8036| 0.0356|
| $c_2$       | 1.8125| 0.0064|
| $d_0$       | 46.8087| 0.1708|
| $d_1$       | 33.1513| 0.1187|
| $d_2$       | 5.7868| 0.0205|
| $e_0$       | 0.7327| 0.0034|
| $e_1$       | 0.4298| 0.0025|
| $e_2$       | 0.0700| 0.0004|

**Note.** — For the fits given by eq. (3) and Table 1.
the absolute magnitudes of RR Lyrae stars with enhanced helium abundances.

4.3. Simple Relations

As in Catelan et al. (2004) and for the bandpasses that show sufficiently tight PL relations (i.e., $i$ and $z$; see Fig. 1), we have computed average PL relations that do not show an explicit dependence on $C_0$. The goal here is to enable an application of our derived PL relations even when observations in the bluer passbands of the SDSS system are not available. We do provide, however, simple relations for colors involving such bluer bandpasses. The resulting relations are as follows:

$$M_z = 0.839 - 1.295 \log P + 0.211 \log Z,$$

with a correlation coefficient $r = 0.97$ and a standard error of the estimate of 0.037 mag;

$$M_i = 0.908 - 1.035 \log P + 0.220 \log Z,$$

with a correlation coefficient $r = 0.95$ and a standard error of the estimate of 0.045 mag;

$$(r - i)_0 = 0.184 + 0.438 \log P + 0.017 \log Z,$$
with a correlation coefficient $r = 0.95$ and a standard error of the estimate of 0.013 mag;

$$(g - r)_h = 0.640 + 0.851 \log P + 0.081 \log Z,$$

(9)

with a correlation coefficient $r = 0.95$ and a standard error of the estimate of 0.027 mag; and

$$(u - z)_h = 2.317 + 1.472 \log P + 0.221 \log Z,$$

(10)

with a correlation coefficient $r = 0.95$ and a standard error of the estimate of 0.045 mag. Note that as a consequence of the large number of stars involved in the fits, the errors in all of the derived coefficient are very small (of order $10^{-4}$ to $10^{-3}$). We performed tests in which quadratic terms were added to these equations, but in no case was the improvement of major significance; the standard errors of the estimates generally changing only in the third decimal place.

4.4. On Applying Our Relations to RR Lyrae Stars

When applying our equation (3) in globular cluster work, the metallicity of the cluster will often be known a priori. However, metallicity estimates may also be unavailable, especially when dealing with field RR Lyrae stars. Yet, for a reliable application of our relations to field stars, an estimate of their metallicities must be provided.

The SDSS system itself may come to our rescue in such a case. We recall that estimates of the RR Lyrae metallicities can be obtained on the basis of their $V$-band light curves using Fourier decomposition (e.g., Jurcsik & Kovács 1996; Jurcsik 1998; Kovács & Kupi 2007; Morgan et al. 2007). Transformation equations between the SDSS system and the Johnson-Cousins system have been provided in the literature (e.g., Karaali et al. 2005), and an updated list of such transformation equations is maintained at the SDSS Web site.\(^3\) For instance, from the current “Lupton set” one finds

$$V = g - 0.2906 (u - g) + 0.0885,$$

(11)

with a $\sigma = 0.013$ mag, and

$$V = g - 0.5784 (g - r) - 0.0038,$$

(12)

with a $\sigma = 0.005$ mag. Thus, on the basis of $V$-band light curves computed from SDSS $u$- and $g$- (or, alternatively, $g$- and $r$-) band magnitudes, one should be able to estimate metallicities for individual RR Lyrae stars through Fourier decomposition. We

\(^3\) See http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.html.
note, in addition, that in a forthcoming paper (M. Catelan & C. Cáceres 2008, in preparation) we will be providing analytical fits that should allow one to estimate metallicity values directly from the SDSS photometry.

The reader should be warned that our relations should be compared against empirical quantities obtained for the so-called equivalent static star. Several procedures have been advanced in the literature for the determination of the latter on the basis of empirically derived magnitudes and colors (e.g., Bono et al. 1995 and references therein). In particular, one should note that according to the hydrodynamical models provided by Bono et al., one should expect differences between temperatures derived from intensity- or magnitude-averaged colors, on the one hand, and those based on the actual color of the equivalent static star, on the other. As a workaround, these authors set forth very useful amplitude-dependent corrections, which become more important the bluer the bandpass. More recently, Marconi et al. (2006) analyzed the problem in the specific case of the SDSS system, concluding that intensity averages, although not perfect, are to be preferred over averages carried out in magnitude units. Unfortunately, tables with amplitude-dependent corrections that would allow one to properly compute magnitudes and colors in the SDSS system for the equivalent static star (i.e., similar to those provided by Bono et al. 1995 in the Johnson-Cousins system) have not yet been provided in the literature. One way or another, the reader should note that \( C_0 \), being a difference between two colors, is presumably affected to a lesser degree than are the colors themselves (see also Cortés & Catelan 2008). Needless to say, observers are also strongly warned against using single-epoch photometry to derive \( C_1 \) values to be used along with our relations.

5. SUMMARY

We have provided the first extensive calibration of the RR Lyrae PL (and PC) relations in the SDSS \( ugriz \) filter system. As in Catelan et al. (2004) we find that these PL relations become progressively tighter for the redder passbands, those in \( i \) and \( z \) appearing particularly promising. We provide very precise relations involving a newly defined, fairly reddening-insensitive pseudocolor \( C_0 \equiv (u - g)_0 - (g - r)_0 \), \( C_0 \)-independent, although less precise, average relations are also provided for those cases in which observations in all five SDSS filters may not be available. Our relations should be especially useful for the calculation of distances and reddenings to even individual field RR Lyrae stars.

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