PUBLICATIONS OF THE ASTRONOMICAL SOCIETY OF THE PACIFIC, **114**:645–649, 2002 June

Light and Color Curves of Six Field RR Lyrae Variable Stars[1]

ALICIA S. DAY AND ANDREW C. LAYDEN

Physics and Astronomy Department, Bowling Green State University, Bowling Green, OH 43403; layden@baade.bgsu.edu

AND

D. W. HOARD,[2] GABRIEL BRAMMER,[3] KATHY COOKSEY,[4] JORGE CUADRA,[5] SHADRIAN HOLMES,[6] ERIKA LABBE,[5] AND RODOLFO MONTEZ, JR.[7]

Cerro Tololo Inter-American Observatory, Casilla 603, La Serena, Chile; hoard@astro.washington.edu

Received 2002 February 26; accepted 2002 March 4

ABSTRACT. We present light curves in the *B*, *V*, and *I* passbands for six field RR Lyrae stars. We derive the stars' intensity-mean magnitudes, light amplitudes, and colors at minimum light. We compare the latter with measurements from other variables and discuss the use of $(V-I)$ color at minimum light as a tool for measuring interstellar reddening. From 15 stars, we find the mean dereddened RR Lyrae color at minimum light to be $(V-I)_0 = 0.57$ mag. The rms scatter of 0.025 mag indicates the precision of this value over a wide range of metallicities and pulsation periods.

1. INTRODUCTION

RR Lyrae variable stars (RRLs) are widely used as distance indicators for old stellar populations. However, many potential targets such as the Galactic bulge, globular clusters, thick-disk RRLs, and the Sagittarius dwarf galaxy lie at low Galactic latitudes where the foreground reddening is high and patchy. For these objects, it is ideal if high-quality reddening estimates can be derived directly from the RRLs themselves, rather than relying on low-resolution reddening maps such as those of Burstein & Heiles (1982) and Schlegel, Finkbeiner, & Davis (1998).

Sturch (1966) found that after small corrections for period and metallicity difference between stars, all RRLs have nearly the same dereddened $(B-V)$ color at minimum light (phase between 0.5 and 0.8). Sturch developed this property into a tool for measuring the interstellar reddening toward RRLs, and Blanco (1992) refined the calibration. Mateo et al. (1995) suggested that $(V-I)$ color at minimum light might make an even better indicator of foreground reddening. However, his suggestion is based on the colors of only 11 RRLs. To test this hypothesis more fully, we are gathering $(V-I)$ observations of a number of high-latitude RRLs. In this paper, we report on data gathered by the 2001 summer students at CTIO.

2. OBSERVATIONS AND REDUCTIONS

Observations were obtained at the Curtis Schmidt telescope at CTIO on six nights in 2001, January 30 and 31 and February 2–5. The central 1024 × 1024 pixels of the SITe 2K No. 5 CCD were used, giving a 40′ field of view. Filters were selected to reproduce the Kron-Cousins *I* and Johnson *B* and *V* passbands. At each telescope pointing, a *BVI* sequence of exposures was obtained. On each of the six nights, twilight sky flats were obtained in each filter. The images were processed in the normal fashion using standard IRAF[8] tasks. Three of the nights were photometric, and Landolt (1992) standard stars were observed over a range of color, air mass, and universal time that bracketed the program stars.

In order to perform differential photometry on nights that were not photometric, we selected nine to 19 comparison stars in the vicinity of each variable star. Instrumental magnitudes were computed from each image using the DAOPHOT task PHOT (Stetson 1994), as implemented in IRAF.

Standard *B*, *V*, and *I* magnitudes for the comparison stars were obtained as follows. Instrumental aperture photometry was measured as above on the photometric nights for both the comparison and Landolt standard stars.[9] For each night, trans-

[1] This research was conducted in part during the 2001 Research Experiences for Undergraduates (REU) and Prácticas de Investigación en Astronomía (PIA) Programs at Cerro Tololo Inter-American Observatory (CTIO).

[2] Director of the 2001 CTIO REU and PIA Programs.

[3] 2001 CTIO REU Program student from Williams College.

[4] 2001 CTIO REU Program student from Valparaiso University.

[5] 2001 CTIO PIA Program student from Pontificia Universidad Catolica de Chile.

[6] 2001 CTIO REU Program student from College of Charleston.

[7] 2001 CTIO REU Program student from University of Texas.

[8] The Image Reduction and Analysis Facility software is distributed by the National Optical Astronomy Observatory.

[9] For the crowded fields of SW Dor, SX Dor, and TX Men, DAOPHOT and ALLFRAME (Stetson 1994) were used to iteratively subtract faint neighboring stars from the images before the aperture photometry was performed.

formation equations of the form

$$m - M = c_0 + c_1 X + c_2 C$$

were constructed, and the coefficients c_i were obtained using least-squares minimization. In the equation, m represents the instrumental magnitude (b, v, or i), M is the standard magnitude from Landolt (1992; B, V, or I), X is the air mass, and C is the color [in the case of B and V, we used $(B-V)$, while $(V-I)$ was used with I]. The rms scatter of the points around each best fit is shown in Table 1, along with the number of stars used in each fit and the number of standard star fields observed that night ($N_{\rm flds}$).

The nightly photometric transformations in Table 1 display a rather large scatter. This is partially due to the undersampling of the stellar profiles by the large CCD pixels (2ʺ.4 pixel^{-1}). We believe that the final calibration of the comparison stars is significantly better: every variable star field was observed at least twice on each photometric night and at least 12 times over the three photometric nights. When averaged together, the magnitudes for each comparison star agreed well, with the standard error of the mean being less than 0.01 mag in most cases.

The comparison star magnitudes were used to calibrate the differential photometry as follows. For each variable star image, we computed N estimates of the magnitude of the variable star, one from each of the N comparison stars. Each estimate used the difference between the variable and comparison star instrumental magnitudes along with the standard magnitude and color of the comparison star. The mean of the N estimates (with the highest and lowest values rejected) was adopted as the final magnitude of the variable star at the time of observation. An electronic table containing the B, V, and I magnitudes and times of observation for each variable is available from A. C. L. upon request.

3. LIGHT CURVES

For each star, the observed data were folded by the period listed in the General Catalogue of Variable Stars (Kholopov 1985). The resulting V-band light curve was fitted with a series of six RR Lyrae templates as described in Layden (1998). Phases for the observed data points were computed from the template fit to the V-band data; template fits to the B- and I-band data were performed at the phases thus fixed. The observed light curves and fitted templates are shown in Figure 1. As suggested by previous investigators, all six stars pulsate in the fundamental mode (Bailey type RRab).

We estimated the time-averaged apparent brightness of each star in each filter from the light curve expressed in intensity units (rather than in magnitudes) using Simpson's Rule. Significant phase gaps exist for most of the stars, so we computed the intensity-mean magnitudes from the fitted templates. The intensity-mean magnitudes ($\langle B \rangle$, $\langle V \rangle$, and $\langle I \rangle$) are presented in Table 2.

TABLE 1
PHOTOMETRIC TRANSFORMATIONS

Night	$N_{\rm flds}$	rms$_B$	N_B	rms$_V$	N_V	rms$_I$	N_I
Jan 31	8	0.034	45	0.041	53	0.052	44
Feb 4	5	0.044	30	0.041	33	0.042	26
Feb 5	8	0.035	33	0.029	41	0.064	40

The pulsation amplitudes in each filter were also computed from the light-curve templates (A_B, A_V, and A_I in Table 2). Table 2 also contains the epoch of maximum light ($E_{\rm max}$), expressed as the heliocentric Julian Date minus 2,451,900 days. The number of observed data points is $N_{\rm obs}$, and the best fitting of the six available templates (Layden 1998) is listed under T. The equatorial coordinates listed in Table 2 were determined from the Digitized Sky Survey and should be accurate to a few arcseconds.

The phase coverage for SX Dor is nearly complete, providing a test of the template fitting method. Intensity-mean magnitudes and pulsation amplitudes were computed from the observed data points and compared with the values derived from the templates. The intensity means for B, V, and I differed by less than 0.01 mag, while differences for the amplitudes were as large as 0.06 mag. This suggests that template fitting is reliable when computing the means, but mismatches between the observed and fitted light-curve shapes can produce noticeable errors in amplitudes (see Fig. 1*b*).

We computed the colors at minimum light from an arithmetic mean of the observed $(B-V)$ and $(V-I)$ values, in magnitude units, having phases between 0.5 and 0.8. The mean values and their standard errors of the mean (ϵ) are reported in Table 3, along with the number of points in the minimum light phase interval. The values for WW and WY Vir should be treated with caution, as the points are few and unevenly distributed across the phase interval.

4. REDDENING CALIBRATION

Sturch (1966) and Blanco (1992) described how apparent $(B-V)$ colors of RRLs at minimum light can be used to measure the amount of interstellar reddening along the line of sight to the star. Mateo et al. (1995) suggested that $(V-I)$ colors might also be used, perhaps with a smaller or negligible metallicity correction.

We estimated the $E(B-V)$ value at the Galactic coordinates of each of our stars from the dust maps of Schlegel et al. (1998). Unfortunately, three of our stars (SW Dor, SX Dor, and TX Men) lie along the line of sight to the Large Magellanic Cloud (LMC), and dust in the LMC artificially inflates the estimated reddening to stars in the foreground. For these stars, we extracted from the Schlegel maps the reddening values for all longitudes in a 2° wide strip centered on the latitude of each variable (the maps were sampled at 0°.25 intervals). Interpolation from 30° wide "windows" on either side of the LMC

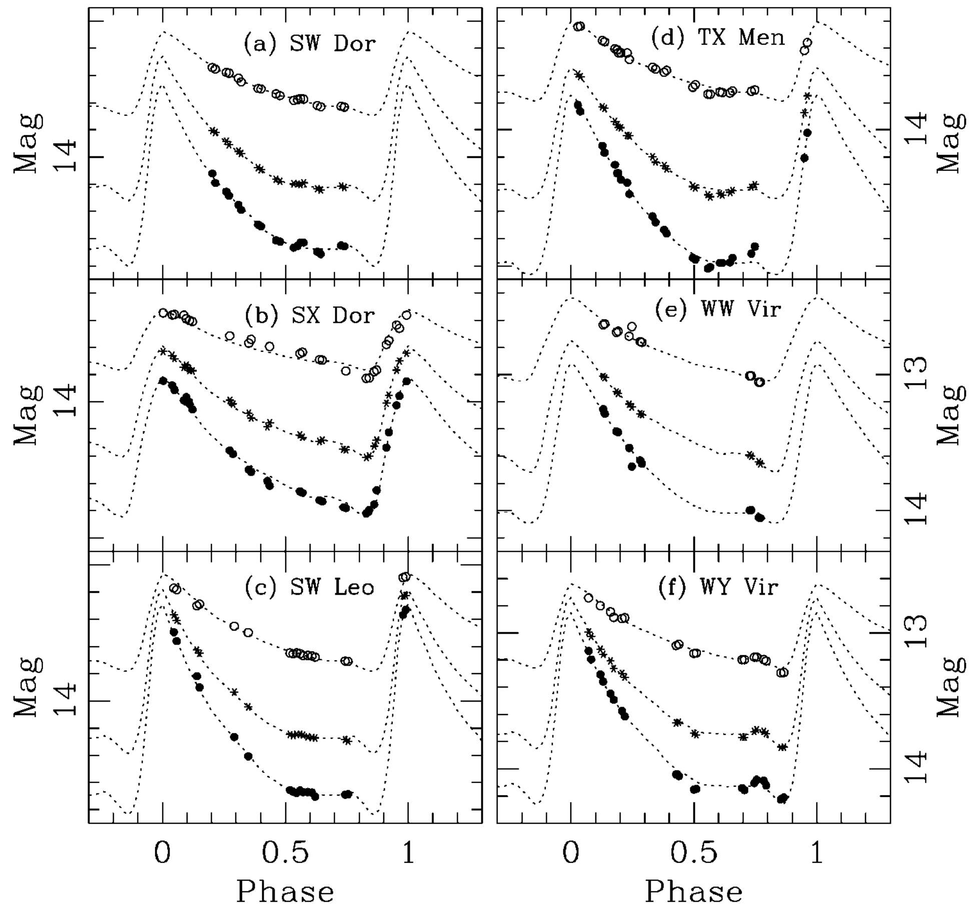

FIG. 1.—Light curves are presented for the six variable stars. Points represent observed data in B (*filled circles*), V (*asterisks*), and I (*open circles*). The dotted curves represent the best-fitting template to the observed data. The vertical axis in each panel spans 2 mag.

yielded a reddening value at the longitude of each variable. The Doradus stars are located near the edge of the LMC, making the interpolation particularly secure for these stars. The scatter about the best fit suggests that the uncertainty in these values is about 0.02 mag. The adopted reddening value for each star is listed in column (7) of Table 3. The dereddened $(B-V)$ and $(V-I)$ color at minimum light for each star is listed in the last two columns of Table 3. We assumed $E(V-I) = 1.28E(B-V)$ (Dean, Warren, & Cousins 1978).

Figure 2 shows the dereddened minimum-light colors as a function of metal abundance for the six RRLs studied herein ([Fe/H] was taken from Layden 1994). The error bars reflect the uncertainty in the observed minimum-light color and in the reddening. Figure 2*a* also shows the $(B-V)_0$ colors of 84 RRLs

TABLE 2
LIGHT-CURVE PARAMETERS

Star	R.A. (J2000.0)	Decl. (J2000.0)	$\langle B\rangle$	$\langle V\rangle$	$\langle I\rangle$	A_B	A_V	A_I	E_{max}	N_{obs}	T
SW Dor	05 02 05.5	−67 16 56	14.29	13.93	13.44	1.34	1.06	0.62	45.4732	18	1
SX Dor[a]	05 03 31.8	−65 42 58	14.39	14.05	13.58	1.03	0.81	0.44	45.6524	30	4
SW Leo	10 55 55.5	−02 58 55	14.23	13.93	13.49	1.55	1.21	0.72	45.2095	18	1
TX Men	05 08 02.0	−79 03 49	14.54	14.14	13.55	1.32	0.96	0.58	45.5881	26	3
WW Vir	13 28 23.8	−05 17 09	13.64	13.29	12.78	1.18	0.97	0.61	45.6556	12	4
WY Vir	13 35 16.2	−06 58 22	13.72	13.44	13.01	1.41	1.11	0.62	45.3725	20	1

NOTE.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

[a] Values for SX Dor obtained from the observed data points were $A_B = 0.97$, $A_V = 0.78$, and $A_I = 0.49$.

TABLE 3
Colors at Minimum Light

Star	$\overline{(B-V)}_{\rm min}$	ϵ_{B-V}	$\overline{(V-I)}_{\rm min}$	ϵ_{V-I}	$N_{\rm min}$	$E(B-V)$	$(B-V)_0$	$(V-I)_0$
SW Dor	0.450	0.006	0.610	0.005	8	0.030	0.420	0.572
SX Dor	0.428	0.006	0.599	0.008	6	0.030	0.398	0.561
SW Leo	0.413	0.004	0.594	0.002	10	0.045	0.368	0.536
TX Men	0.506	0.008	0.736	0.007	9	0.060	0.446	0.659
WW Vir	0.404	0.003	0.589	0.004	4	0.031	0.373	0.549
WY Vir	0.383	0.006	0.559	0.010	8	0.028	0.355	0.523

compiled by Blanco (1992). The reddening for each star was computed from Schlegel et al. (1998). To minimize errors in high-reddening stars, only stars more than 20° from the Galactic plane are plotted. Similarly, Figure 2*b* shows the $(V-I)_0$ colors of 10 high-latitude RRLs compiled by Mateo et al. (1995). The literature data in both panels are almost entirely from photoelectric photometry of bright stars and have slightly better precision than our CCD photometry. The metallicities were taken from Fernley et al. (1998) or, if unavailable, from Layden (1994) or Blanco (1992).

Our six stars agree quite well with the $(B-V)_0$ of the stars from the literature with the exception of TX Men ([Fe/H] = −2.48), the star with the most uncertain reddening. Our stars even match the period dependence of the literature stars, as shown by the tendency for like symbols to congregate in Figure 2*a* (see the symbol key in Fig. 2*b*). This suggests that our *B*- and *V*-band photometry is of high quality.

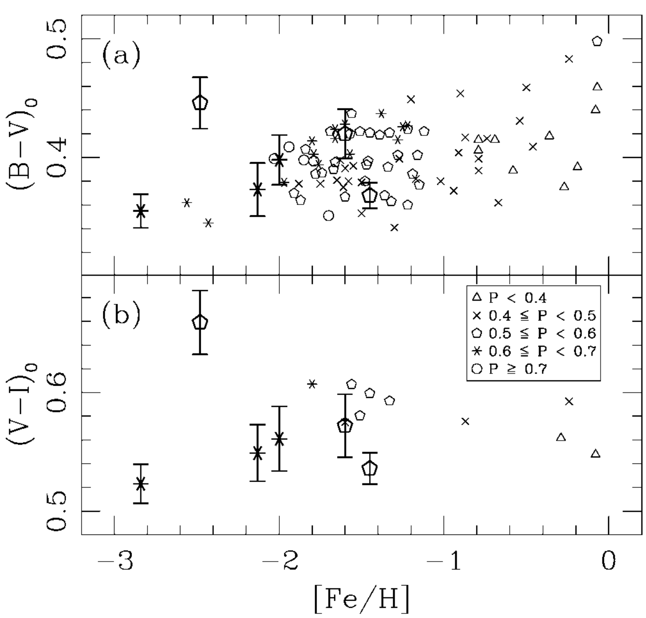

Fig. 2.—Dereddened minimum-light colors as a function of metallicity (*a*) for $(B-V)$ and (*b*) for $(V-I)$. In both panels, the symbols indicate the period of each star as shown in the key. Bold symbols mark the six RRLs from this study.

The $(V-I)_0$ values of our RRLs shown in Figure 2*b* follow the color-metallicity trend seen for $(B-V)_0$ in Figure 2*a* (again, with the exception of TX Men). However, the 10 literature stars seem to define a trend with the opposite slope. The discrepancy could result from our imperfect *I*-band photometric calibrations (Table 1). With improved calibrations, we might find that our RRLs follow the rather tight relation defined by the literature stars. Another possibility is that the true color-metallicity relation in $(V-I)_0$ has a similar slope and scatter to that seen for $(B-V)_0$ and that the small sample of stars available in the literature gives a deceptive picture of the true relation. This possibility would be revealed as we gather $(V-I)_0$ data on additional RRLs.

Sturch (1966) and Blanco (1992) developed relations between $(B-V)_0$, metallicity, and period. Given the scatter in Figure 2*b*, it seems premature to attempt a multivariate fit to the $(V-I)_0$ data. A simple mean of the 15 points (TX Men excluded) yields $\overline{(V-I)}_0 = 0.57$ with an rms scatter of 0.025 mag. Until the above issues are resolved, this can be considered a working calibration for the minimum-light reddening method in $(V-I)_0$. The small star-to-star scatter suggests that the method works at least as well in $(V-I)$ as it does in $(B-V)$, as was originally suggested by Mateo et al. (1995).

To summarize, we have obtained light curves in *B*, *V*, and *I* for six field RR Lyrae stars. We derived the stars' intensity-mean magnitudes, light amplitudes, and colors at minimum light. Our new data confirm that $(V-I)$ color at minimum light is a promising tool for measuring interstellar reddening along the line of sight to RRLs, which thus makes them even more reliable distance indicators.

This work represents partial fulfillment of the requirements for a minor degree in Astronomy at Bowling Green State University. This research was conducted in part during the 2001 Research Experiences for Undergraduates (REU) and Prácticas de Investigación en Astronomía (PIA) Programs at CTIO. The CTIO REU Program is funded by the National Science Foundation (NSF). The CTIO PIA Program is funded by CTIO. CTIO is operated by AURA, Inc., under cooperative agreement with the NSF. This research made use of the Digitized Sky Survey and the Astrophysics Data System Abstract Service. We thank the anonymous referee for helpful comments.

REFERENCES

Blanco, V. M. 1992, AJ, 104, 734
Burstein, D., & Heiles, C. 1982, AJ, 87, 1165
Dean, J. F., Warren, P. R., & Cousins, A. W. J. 1978, MNRAS, 183, 569
Fernley, J., Barnes, T. G., Skillen, I., Hawley, S. L., Hanley, C. J., Evans, D. W., Solano, E., & Garrido, R. 1998, A&A, 330, 515
Kholopov, P. N. 1985, General Catalogue of Variable Stars (4th ed.; Moscow: Nauka)
Landolt, A. U. 1992, AJ, 104, 340
Layden, A. C. 1994, AJ, 108, 1016
———. 1998, AJ, 115, 193
Mateo, M., Udalski, A. Szymanski, M., Kaluzny, J., Kubiak, M., & Krzeminski, W. 1995, AJ, 109, 588
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Stetson, P. B. 1994, PASP, 106, 250
Sturch, C. 1966, ApJ, 143, 774