The Intrinsic Colors of RR Lyrae Variables: A Means to Determine Interstellar Reddening

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ABSTRACT

We present refined BVI light curves for six field RR Lyrae variable stars. The refinements include new data and improved photometric calibration compared to our previous work. For each star, we derive the intensity-mean magnitudes, light amplitudes, and colors at minimum light. We combine our results with literature data to estimate the mean, dereddened RR Lyrae color at minimum light to be $\overline{(V-I)_{0,min}} = 0.58 \pm 0.02$ mag with a star to star scatter of 0.024 mag. Any dependence of color on metallicity is too weak to be formally detected with the available data. One of our stars exhibits the Blazhko Effect. The star's minimum light color is unchanged at the two observed phases of the star's Blazhko cycle, while the maximum light color changed significantly. This insensitivity further supports the reliability of minimum light $(V - I)$ colors as a tool for measuring interstellar reddening.

Subject headings: stars: horizontal branch — stars: variables: other — dust, extinction

1. Introduction

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

Sturch (1966) found that, after small corrections for period and metallicity differences between stars, all RRL 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 RRL, and Blanco (1992) refined the calibration. Day et al. (2002) presented new BVI light curves for six RRL to test the hypothesis of Mateo et al. (1995), who suggested that $(V-I)$ color at minimum light might make an even better indicator of foreground reddening. Day et al. (2002) found the mean, dereddened $(V-I)$ color at minimum light to be 0.57 mag with a rms scatter of 0.025 mag, with at best a weak dependence on metallicity or period.

However, the data from Day et al. (2002) suffered from two deficiencies. First, the phase coverage of several of the stars was rather sparse across the minimum light range. Second, the photometric uncertainty and standard star transformations were compromised somewhat by undersampling due to the large CCD pixels employed. In this paper, we report on new data gathered to correct both these deficiencies, and to update the mean, dereddened $(V-I)$ color calibration at minimum light described above.

2. Observations and Reductions

Images were obtained at the 0.9-m telescope at Cerro Tololo Inter-American Observatory (CTIO) on six nights over 2002 January 22-27. The Tek#3 2048^2 CCD was used, giving a field of view 13.5 arcmin on a side with a scale of 0.40 arcsec pixel^{-1}. The filters were selected to reproduce the Kron-Cousins I and Johnson B and V passbands. Each time the telescope was pointed to a particular variable, a BVI sequence of images was obtained. The images were overscan corrected, trimmed, and bias subtracted in the normal fashion, and were flat-fielded using twilight sky flats.

The 0.9-m observing setup has both advantages and disadvantages compared with the setup used by Day et al. (2002). The latter used the CTIO Schmidt telescope, which provided a 40 arcmin field and 2.4 arcsec pixels. The stellar profiles, typically 1–2 arcsec fwhm, were undersampled by the Schmidt pixels, but were properly sampled in the 0.9-m data. This led to better photometric accuracy in the 0.9-m data. Also, iterative subtraction of faint stars near the comparison stars using DAOPHOT (Day et al. 2002) proved unnecessary in the better-sampled 0.9-m images. However, the 0.9-m's smaller field of view limited the number of bright, uncrowded comparison stars available around each variable to 8–11 stars, compared with the 9–19 comparison stars used with the Schmidt. Nevertheless, the 0.9-m field provided ample comparison stars, and the internal photometric accuracy of the 0.9-m data proved to be superior to that of the Schmidt.

These comparison stars were used to perform differential photometry with respect to the variable on nights that were not photometric. Two of the six nights were photometric, and several Landolt (1992) standard star fields were observed on each night at a range of airmasses and times bracketing the RRL observations. These images enabled us to determine the standard B, V, and I magnitudes for the comparison stars, and thereby calibrate the differential photometry. First, instrumental aperture photometry was measured for both the comparison stars and the Landolt standard stars using the DAOPHOT task PHOT (Stetson 1987). Then, for each night in each filter we constructed transformation equations of the form

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

where m is a star's measured instrumental magnitude (b, v, or i), M is its known standard magnitude from Landolt (1992; B, V, or I), X is the airmass, and C is the color ($C = B - V$ in the case of B and V, while $C = V - I$ for I). The c_i coefficients were obtained by least-squares fitting. The rms scatter around the best fit for each night is shown in Table 1, along with the number of stars used in each fit ($N_{B,V,I}$) and the number of standard fields observed each night (N_{flds}). Table 1 displays a smaller rms scatter than was obtained using the Schmidt (See Table 1 of Day et al. 2002) by almost a factor of two, indicating that our new photometry is tied more closely to the Landolt (1992) system.

Once these equations were determined we applied them to all of the comparison stars and averaged the results to give us the final, standard B, V, and I magnitudes for each comparison star. The comparison star magnitudes were then used to calibrate the 0.9-m differential photometry following the procedures described in Day et al. (2002). We also recalibrated the differential photometry taken with the Schmidt (Day et al. 2002) using these revised comparison star magnitudes, thereby improving the quality of the Schmidt data and expanding the overall data set. These data are presented in Table 2.

3. Light Curves

The data for each star were then folded by the period specified in the General Catalogue of Variable Stars (Kholopov 1985), listed in column 2 of Table 3. By combining the 2001 (Schmidt) data set with the 2002 (0.9-m) set, we obtained more complete phase coverage for each star, except in the case of T Men which was not observed by Day et al. (2002).

The resulting light curves are shown in Figure 1. To help exhibit the stars' behavior, each light curve was fit with a series of six RRL light curve templates as described in Layden (1998) in each of B, V, and I, with the best fitting template shown in Figure 1.

For most of the stars in Figure 1, the fitted template describes the light curve shapes for both the 2001 (Schmidt) and 2002 (0.9-m) data sets. The exception is SX Dor, which displays different light curve shapes and amplitudes for the two data sets. We interpret this to mean that SX Dor exhibits the Blazhko Effect, in which these parameters change gradually in a cycle with a periodicity much longer than the pulsation cycle (Blazhko 1907).

We estimated intensity-mean magnitudes ($\langle B \rangle$, $\langle V \rangle$, and $\langle I \rangle$) and pulsation amplitudes (A_B, A_V, and A_I) for each star from the observed data (for WW Vir, which lacks data around maximum and minimum light, we obtained these values from the fitted templates instead). These values are presented in Table 3 along with the epoch of maximum light, E_{max}, expressed as the heliocentric Julian date minus 2,450,000 days, and the number of observed data points for each star, N_{obs}. For SX Dor, we present separate results for the 2001 (Schmidt) and 2002 (0.9-m) data to describe the star's behavior at these distinct points in its Blazhko cycle.

Finally, we computed the colors at minimum light via an arithmetic mean of the observed $(B - V)$ and $(V - I)$ data values, in magnitude units, having phases between 0.5 and 0.8. The mean values and their standard errors of the mean are reported in columns 3 and 4 of Table 4, along with the number of points in the minimum light phase interval, N_{min}. For WW Vir we used the observed data instead of the fitted template since the phase is adequately covered at minimum light.

4. Reddening Calibration

We can use the apparent colors of our program stars in concert with reddening values taken from the literature to compute the stars' intrinsic, dereddened colors. These in turn can be used to verify and refine the dereddened color calibrations described by Sturch (1966), Blanco (1992), and Day et al. (2002).

Reddening values for SW Leo, WW Vir, and WY Vir were taken directly from the Schlegel, Finkbeiner, & Davis (1998) reddening maps. Reddening values for SW Dor, SX Dor, and T Men, which lie in front of the dust-rich Large Magellanic Cloud (LMC), were estimated by interpolating Schlegel, Finkbeiner, & Davis (1998) reddening values at constant latitude across the face of the LMC as described in Day et al. (2002). The adopted $E(B-V)$ reddenings are presented in Table 4. The star TX Men was dropped from the 0.9-m study because it was more centrally located in the LMC and its interpolated reddening was correspondingly uncertain. It was replaced with T Men, which is closer to LMC edge. The dereddened $(B-V)$ and $(V-I)$ colors at minimum light for each star, computed assuming $E(V-I) = 1.3\ E(B-V)$, are listed in the last two columns of Table 4.

Figure 2 shows the dereddened color curves for all six RRL. The $(B-V)_0$ curves have a smaller scatter in color at minimum light than the $(V-I)_0$ curves (rms = 0.019 mag and 0.031 mag, respectively). This could arise from the larger error found in our I-band transformation relations (see Table 1), or from increased contamination by background LMC stars which are more visible in the I-band images. However, individual stars appear to display fairly flat behavior in both $(B-V)_0$ and $(V-I)_0$ across the minimum light phase interval (see Figure 2), supporting the idea that this is an effective range of phases on which to base mean color and reddening estimates.

Figure 3 shows the dereddened color curves specifically for the Blazhko star SX Dor. This star provides us with an opportunity to study whether the Blazhko Effect influences the star's color and the reddening estimated from it. Around maximum light, the colors obtained in 2001 and 2002 deviate significantly, whereas at minimum light the deviation is small or nonexistent. The latter is quantified in the last columns of Table 4. This further supports that idea that basing colors on the phase range 0.5–0.8 provides more reliable reddening estimates than on wider phase ranges. Further study of this and other Blazhko stars would help to clarify and strengthen this result.

Figure 4 shows the dereddened minimum-light colors as a function of metal abundance (Layden 1994) for the six RRLs studied herein. SX Dor is plotted twice to reflect its position at the two different phases of its Blazhko cycle. Figure 4a also shows the minimum-light $(B-V)_0$ colors of 84 RRL which were taken from Blanco (1992) and dereddened using $E(B-V)$ values from Schlegel, Finkbeiner, & Davis (1998). To minimize errors in reddening, only stars more that 20 deg from the Galactic plane are plotted. Similarly, Figure 4b shows the minimum-light $(V-I)_0$ colors of ten high-latitude RRL from Liu & Janes (1989). The literature data in both panels are mostly from photoelectric photometry of bright stars and have slightly better precision than our CCD photometry.

As was found by Day et al. (2002), our new RRL agree well with the $(B-V)_{0,min}$ values of stars from the literature, following their color-metallicity-period behavior. This is a good indication that our BV photometry is on the same photometric system as the literature stars, and supports the reddening relation derived from those data by Blanco (1992).

With our recalibration of the 2001 (Schmidt) data and the addition of the 2002 (0.9-m) data, our $(V-I)_{0,min}$ values shown in Figure 4b are more consistent with those of the literature than were the data from Day et al. (2002). Stars with similar periods now tend to congregate more noticeably, and the program and literature data sets appear to share a common slope, whereas the slopes trended in the opposite senses in Day et al. (2002). On average, our data appear to be ∼0.03 mag bluer at a given metallicity than the literature data. This may represent a systematic difference in our photometric zeropoints, or it may reflect the small sample sizes.

Assuming for now that our photometry shares a common zeropoint with that of Liu & Janes (1989), we can characterize the relationship between intrinsic color and metallicity. A simple mean of the 16 stars in Figure 4b yields $\overline{(V-I)_{0,min}} = 0.579 \pm 0.006$ mag with an rms scatter of 0.024 mag. This result is very similar to that of Day et al. (2002), who found $\overline{(V-I)_{0,min}} = 0.57$ with an rms scatter of 0.025 mag. If we seek a color-metallicity relation, we obtain $\overline{(V-I)_{0,min}} = (0.569 \pm 0.009) - (0.008 \pm 0.006)$ [Fe/H] with an rms of 0.024 mag. Though the slope coefficient is not formally significant, it is affected substantially by the outlier star WY Vir. Removing this star makes the slope coefficient marginally significant (-0.015 ± 0.007 mag dex^{-1}). Interestingly, the slope appears to be in the sense opposite that found for $\overline{(B-V)_{0,min}}$ (Blanco 1992), with more metal rich stars appearing slightly bluer. However, more RRL spanning a wide range of metallicities are required before the slope coefficient can be determined properly, and for now we adopt use of the simple mean described above. While the internal scatter is small, systematic zeropoint errors of ∼0.02 mag are possible, so we advocate $\overline{(V-I)_{0,min}} = 0.58 \pm 0.02$ mag for use when computing interstellar reddenings.

In summary, we have presented BVI light curves for six field RR Lyrae stars. We recalibrated data from Day et al. (2002) and obtained additional data to achieve light curves that have more complete phase coverage and which are more closely tied to the photometric system defined by Landolt (1992). The light curves yielded intensity-mean magnitudes, light amplitudes, and colors at minimum light. The latter enabled us to improve the minimum-light $(V-I)_0$ color calibration derived by Day et al. (2002), and thereby improve this method for obtaining interstellar reddenings. Our discovery that one of our stars, SX Dor, exhibits the Blazhko Effect allowed us to test the reliability of reddenings using this method across different phases of the star's Blazhko cycle. We found reddenings based on colors at minimum light are minimally affected by Blazhko variations, and that color variations are most pronounced at maximum light.

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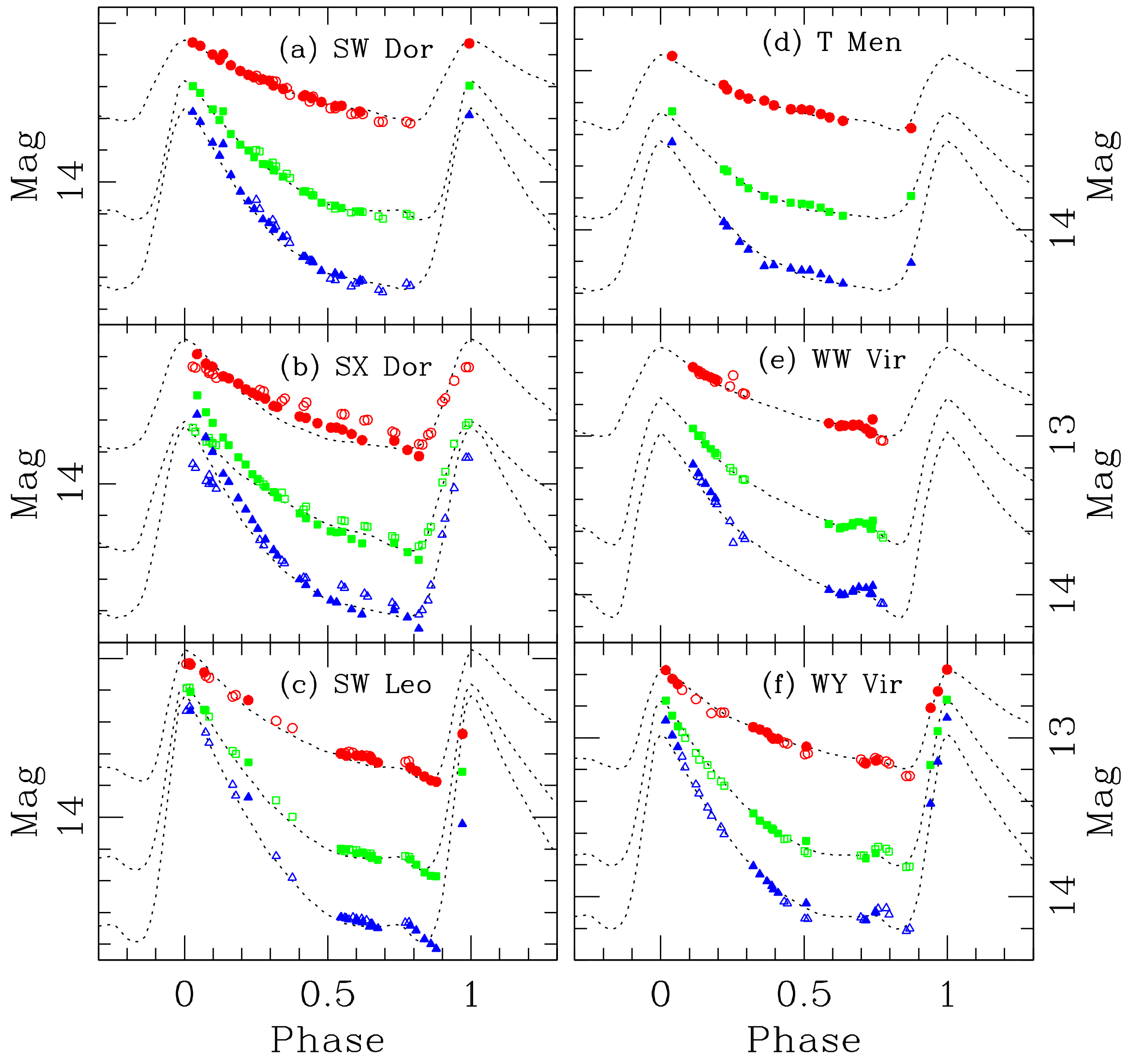

Fig. 1.— Light curves for the six variable stars. Points represent observed data in B (triangles), V (squares), and I (circles). Data obtained during the 2001 (Schmidt) and 2002 (0.9-m) seasons are indicated by open and filled points, respectively. The dotted curves represent the best fitting template to the observed data. In each panel, the vertical axis spans two magnitudes.

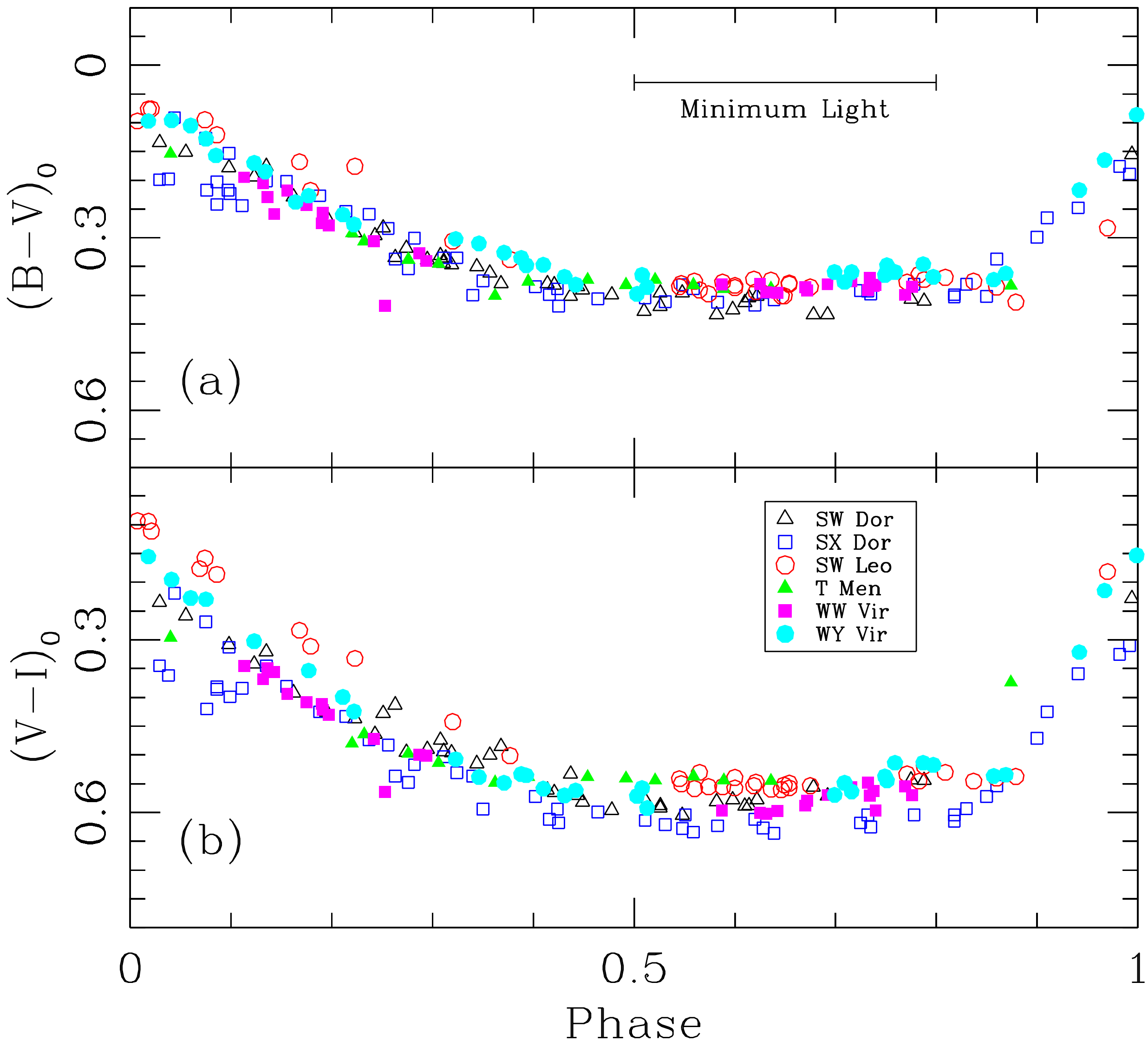

Fig. 2.— Dereddened color curves are presented for the six variable stars using the data found in Figure 1. Different symbols are used to represent the individual variable stars as shown in the key.

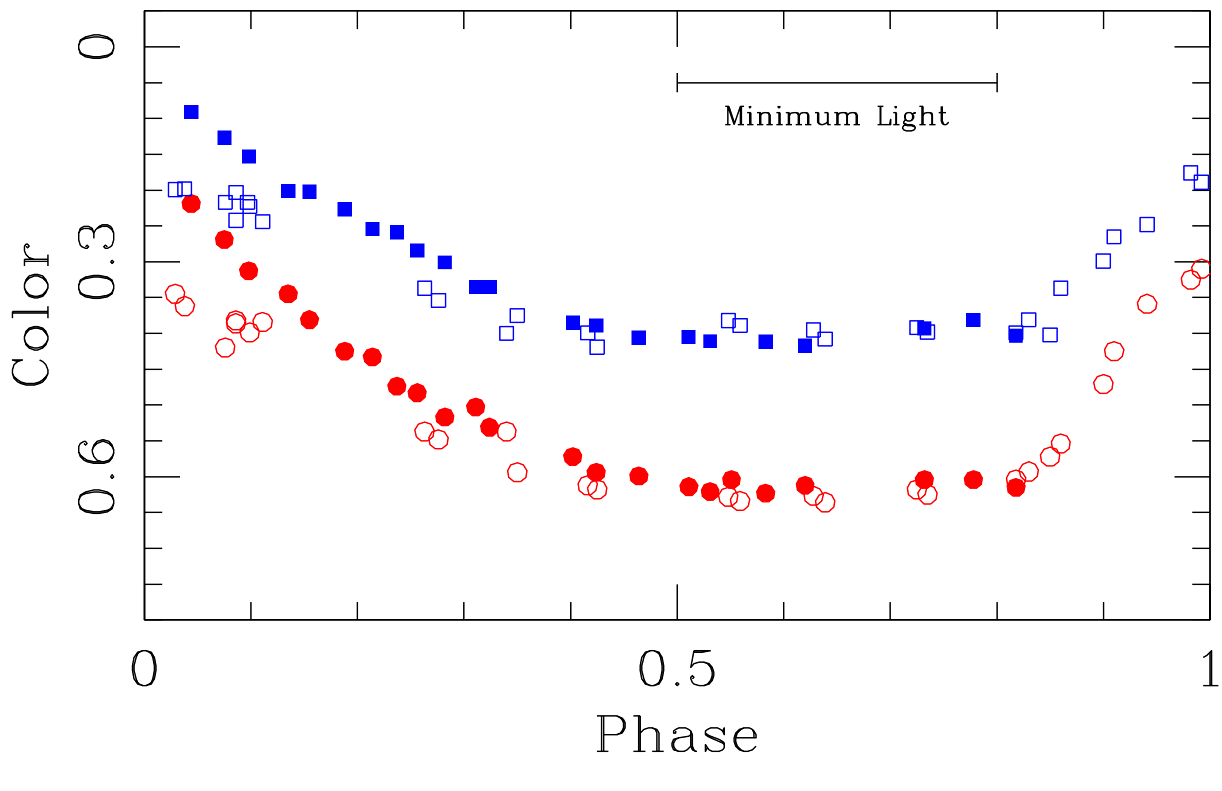

Fig. 3.— The dereddened color curves are presented for SX Dor, a star exhibiting the Blazhko effect. Squares indicate $(B-V)_0$ while circles indicate $(V-I)_0$ data. Open and filled symbols indicate data obtained in 2001 (Schmidt) and 2002 (0.9-m), at different points in the star's Blazhko cycle (see Figure 1b). The colors at minimum light are very similar at these two points in the Blazhko cycle.

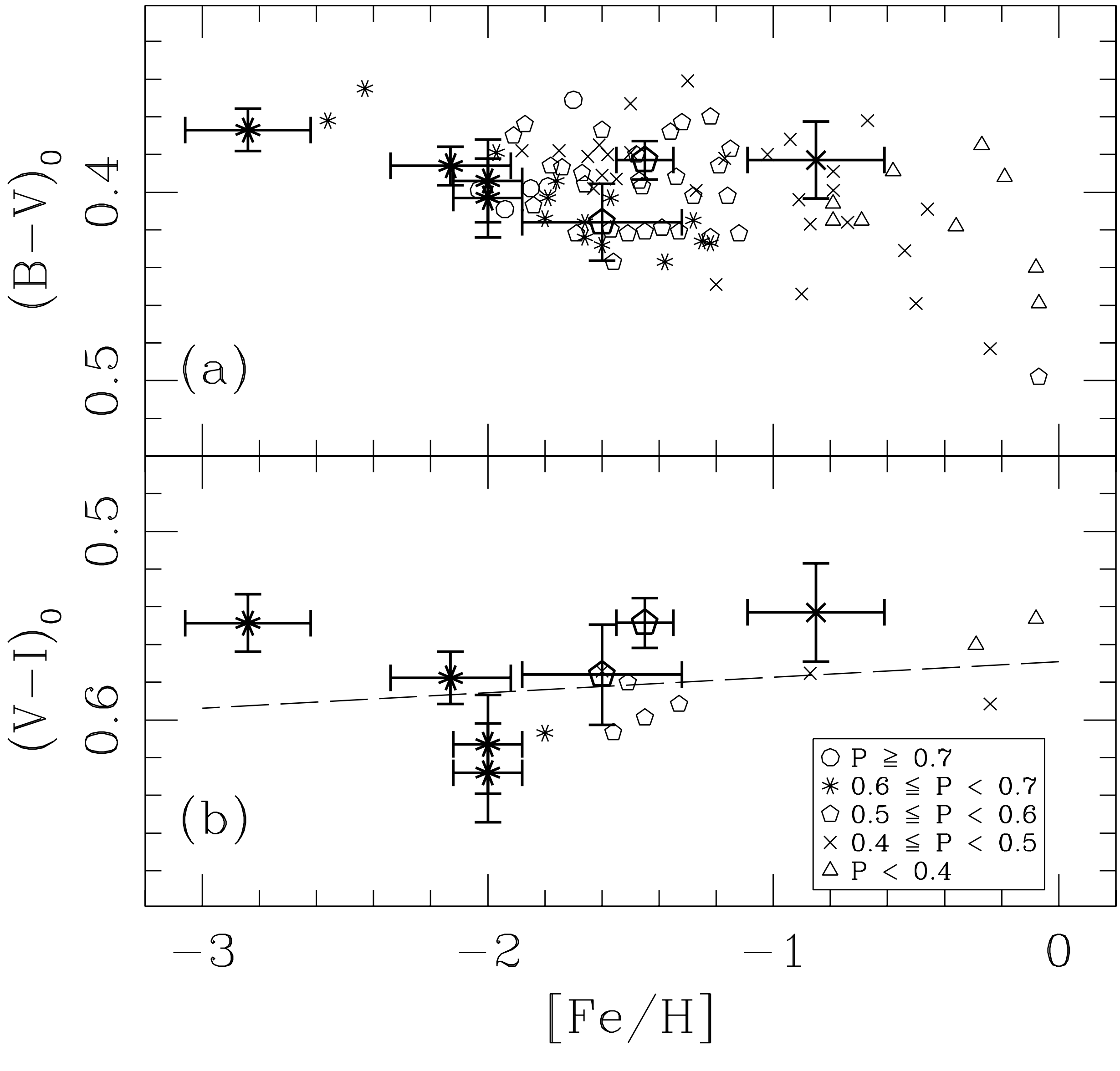

Fig. 4.— Dereddened minimum-light colors are shown as a function of metallicity. In both panels, the symbols indicate the period of each star as shown in the key. Bold symbols mark the six RRL from this study, while light symbols indicate data taken from the literature. The dashed line in panel (b) indicates the best-fit line to the data.

Table 1. Photometric Transformations

Night	N_{flds}	rms_B	N_B	rms_V	N_V	rms_I	N_I
2002 Jan 22	6	0.015	34	0.016	43	0.037	47
2002 Jan 25	5	0.019	17	0.027	25	0.030	18

Table 2. Time Series Photometry

Star	HJD[a]	Phase	B	σ_B	V	σ_V	I	σ_I
SW Dor	2297.57349	0.295	14.259	0.008	13.891	0.008	13.362	0.008
SW Dor	2297.59912	0.344	14.347	0.002	13.967	0.004	13.413	0.003
SW Dor	2297.63965	0.421	14.470	0.003	14.058	0.002	13.454	0.002
SW Dor	2297.65186	0.444	14.496	0.003	14.081	0.002	13.472	0.003

[a]Heliocentric Julian date after subtraction of 2,450,000 days.

Note. — The complete version of this table is in the electronic edition of the journal. The printed edition contains only a sample.

Table 3. Light Curve Parameters

Star	Period	$\langle B\rangle$	$\langle V\rangle$	$\langle I\rangle$	A_B	A_V	A_I	E_{max}	N_{obs}	Comment
SW Dor	0.5254	14.18	13.86	13.39	1.14	0.84	0.51	2300.5710	40	–
SX Dor	0.631486	14.38	14.03	13.48	0.99	0.78	0.49	1945.6593	29	2001 data only
SX Dor	0.631486	14.32	14.03	13.53	1.35	1.04	0.64	2300.5333	23	2002 data only
SW Leo	0.554152	14.18	13.88	13.44	1.53	1.19	0.75	2301.5007	35	–
T Men	0.409841	14.02	13.68	13.18	0.89	0.66	0.45	2300.4774	14	2002 data only
WW Vir	0.6515827	13.62	13.28	12.76	1.17	0.93	0.56	2301.3999	27	From fitted LC
WY Vir	0.609354	13.70	13.41	12.95	1.34	1.05	0.67	2301.8384	35	–

Table 4. Colors at Minimum Light

Star	[Fe/H]	$\overline{(B-V)}_{min}$	$\overline{(V-I)}_{min}$	N_{min}	$E(B-V)$	$(B-V)_{0,min}$	$(V-I)_{0,min}$
SW Dor	–1.60	0.446 ± 0.004	0.615 ± 0.005	13	0.030 ± 0.020	0.416 ± 0.020	0.576 ± 0.027
SX Dor[a]	–2.00	0.424 ± 0.009	0.667 ± 0.003	6	0.030 ± 0.020	0.394 ± 0.022	0.628 ± 0.026
SX Dor[b]	–2.00	0.433 ± 0.006	0.652 ± 0.003	6	0.030 ± 0.020	0.403 ± 0.021	0.613 ± 0.026
SW Leo	–1.45	0.428 ± 0.002	0.607 ± 0.003	19	0.045 ± 0.010	0.383 ± 0.010	0.549 ± 0.013
T Men	–0.85	0.423 ± 0.004	0.595 ± 0.002	4	0.040 ± 0.020	0.383 ± 0.020	0.543 ± 0.026
WW Vir	–2.13	0.417 ± 0.002	0.618 ± 0.005	14	0.031 ± 0.010	0.386 ± 0.010	0.578 ± 0.014
WY Vir	–2.84	0.395 ± 0.005	0.585 ± 0.008	11	0.028 ± 0.010	0.367 ± 0.011	0.549 ± 0.015

[a]Data from 2001 (Schmidt) only.

[b]Data from 2002 (0.9-m) only.