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# THE DETERMINATION OF REDDENING FROM INTRINSIC $V - R$ COLORS OF RR LYRAE STARS

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## ABSTRACT

New  $R$ -band observations of 21 local field RR Lyrae variable stars are used to explore the reliability of minimum light  $(V - R)$  colors as a tool for measuring interstellar reddening. For each star,  $R$ -band intensity mean magnitudes and light amplitudes are presented. Corresponding  $V$ -band light curves from the literature are supplemented with the new photometry, and  $(V - R)$  colors at minimum light are determined for a subset of these stars as well as for other stars in the literature. Two different definitions of minimum light color are examined, one which uses a Fourier decomposition to the  $V$  and  $R$  light curves to find  $(V - R)$  at minimum  $V$ -band light,  $(V - R)_{\min}^F$ , and the other which uses the average color between the phase interval 0.5–0.8,  $(V - R)_{\min}^{\phi(0.5-0.8)}$ . From 31 stars with a wide range of metallicities and pulsation periods, the mean dereddened RR Lyrae color at minimum light is  $(V - R)_{\min,0}^F = 0.28 \pm 0.02$  mag and  $(V - R)_{\min,0}^{\phi(0.5-0.8)} = 0.27 \pm 0.02$  mag. As was found by Guldenschuh et al. using  $(V - I)$  colors, any dependence of the star’s minimum light color on metallicity or pulsation amplitude is too weak to be formally detected. We find that the intrinsic  $(V - R)$  of Galactic bulge RR Lyrae stars are similar to those found by their local counterparts and hence that bulge RR0 Lyrae stars do not have anomalous colors as compared to the local RR Lyrae stars.

**Key words:** dust, extinction – Galaxy: center – stars: abundances – stars: distances – stars: horizontal-branch – stars: Population II

*Online-only material:* machine-readable and VO tables

## 1. INTRODUCTION

RR Lyrae variables play an important role in the determination of distances to the Galactic center, globular clusters, and neighboring galaxies. This information is of fundamental importance in the study of the galactic structure and dynamics. In addition, RR Lyraes provide an excellent sample of stars to investigate kinematics in the galaxy (see, e.g., Beers et al. 2000; Layden et al. 1996; Dambis & Rastorguev 2001). Their pulsational properties combined with an almost constant absolute magnitude make them excellent tracers of the old stellar populations.

As bulge RR Lyrae variables are among the oldest and most metal poor stars in the bulge, their distribution, and signature are of considerable importance in determining the mix of populations in the Galactic bulge, and vital to our understanding of the nature of the bulge itself. RR Lyrae variables have also advanced our understanding especially of the halo and thick disk components of the Milky Way. For example, the Sloan Digital Sky Survey (SDSS; Ivezić 2000) and QUEST (Vivas & Zinn 2006) surveys have used RR Lyrae stars to find complex substructure in the Galactic halo, thick disk, and thin disk distribution. Many irregular structures, such as the Sgr dwarf tidal stream in the halo and the Monoceros stream closer to the Galactic plane, have strengthened the notion that the Milky Way is a complex and dynamical structure that is still being shaped by the merging of neighboring smaller galaxies.

Regardless of how convenient a distance indicator may be, without knowing reddening, accurate distances cannot be found. Especially the central regions of the Galaxy and other low latitude areas suffer from severe crowding and high, patchy, reddening. It would be especially useful to have a method for determining interstellar reddening directly from the RR Lyrae,

rather than depending on extinction maps in a certain area of the sky with perhaps low resolution and large uncertainties.

The minimum light color of RR0 Lyrae variables has been used to estimate their line-of-sight reddenings. This is based on a concept originally developed by Sturch (1966) to investigate  $E(B - V)$  and refined by Blanco (1992). Blanco (1992) used 22 stars to derive a relationship between an RR Lyrae variable’s line-of-sight color excess,  $E(B - V)$ , as a function of the RR Lyrae’s period, metallicity, and minimum  $E(B - V)$  color. An investigation of  $E(V - I)$  was performed by Mateo et al. (1995) with an 11 star sample and expanded on by Guldenschuh et al. (2005) who used 16 RR0 Lyrae variables. They found that  $E(V - I)$  depends upon only minimum  $(V - I)$  color. Guldenschuh et al. (2005) concluded that the intrinsic minimum light color of RRab variables is  $(V - I)_{\min,0}^{\phi(0.5-0.8)} = 0.58 \pm 0.02$ , with very little dependence on period or metallicity for periods between 0.39 and 0.7 days and metallicities in the range  $-3 \leq [\text{Fe}/\text{H}] \leq 0$ . These studies define minimum light color to be the average color over the phase range 0.5–0.8, designated here as i.e.,  $(V - I)_{\min}^{\phi(0.5-0.8)}$  for the color  $(V - I)$ .

Most recently, Kunder et al. (2008) did a study on the determination of  $E(V - R)$  from RR0 Lyrae stars minimum light color using 11 stars and data in the literature. They defined minimum light color not by  $(V - R)_{\min}^{\phi(0.5-0.8)}$ , but by the  $(V - R)$  at minimum  $V$ -band light,  $(V - R)_{\min}^F$ . Fourier fits to both the  $V$ - and  $R$ -band data were administered to determine this quantity. This definition of minimum light was used because Kanbur & Fernando (2004) observed that the RR0 Lyrae in the LMC display period–color and amplitude–color relations that are flat at  $(V - R)_{\min}^F$ . Kunder et al. (2008) found that  $(V - R)_{\min}^F$  is a better diagnostic for determining intrinsic colors than  $(V - R)_{\min}^{\phi(0.5-0.8)}$ , because it is not as correlated

with the RR Lyrae's amplitude. Kunder et al. (2008) found an intrinsic  $(V - R)_{\min}^F$  to be  $0.28 \pm 0.014$  mag for periods between 0.39 and 0.6 days and metallicities in the range  $-1.7 \leq [\text{Fe}/\text{H}] \leq -0.01$ .

In this paper, we report on new data gathered to refine the relationship of reddening at minimum light  $(V - R)$  color. Although  $V$ -band photometry of RR Lyrae stars is quite common in the literature, this is not the case for the  $R$  band. Here new  $R$ -band observations are obtained to triple the sample of RR Lyrae stars available for intrinsic  $(V - R)_{\min}$  determinations. Our 21 program stars were chosen to span a large range of  $V$  amplitudes, pulsational periods, and metallicities. The  $V$ -band photometry for these stars is taken from various sources in the literature, including Piersimoni et al. (1993), Stiepeń (1972), Jones et al. (1987), and Bookmeyer et al. (1977), the Behlen Variable Star Survey (Schmidt 1991, 1995), and the All Sky Automated Survey (ASAS) database (Pojmanski 2002). Both methods of determining minimum light are investigated,  $(V - R)$  at minimum  $V$ -band light,  $(V - R)_{\min}^F$ , and the average color over the phase range 0.5–0.8,  $(V - R)_{\min}^{\phi(0.5-0.8)}$ . This reddening procedure can be applied to the thousands of RR Lyrae stars found in the MACHO database.

The MACHO Project was designed to search for MACHOs through gravitational microlensing. Their project surveyed the same fields in the sky of the Large and Small Magellanic Clouds and the bulge of the Milky Way. Now, after its eight years of operation from 1992 to 1999, the MACHO photometric database is an unprecedented resource for the study of stellar variability. Kunder et al. (2008) found 3674 RR0 Lyrae stars in the MACHO database, that were imaged simultaneously by the MACHO team in the  $b_M$  and  $r_M$  filters. These have been transformed to standard Johnson's  $V$  and Kron-Cousins  $R$  (Alcock et al. 1999). Using these RR Lyrae as standard candles, they can be used to map the bulge and obtain its three-dimensional structure, giving clues, and constraining models on the formation of the Milky Way Galaxy. As with any study of the Galactic bulge, interstellar reddening estimates are essential to begin investigations in a quantitative manner.

Recently, there has been some controversy as to if RR Lyrae variables can be used to measure reddening from their minimum light colors and if their absolute magnitudes are environment dependent (i.e., if the intrinsic properties of RR Lyrae vary with the composition and age of the system/environment in which they reside). Collinge et al. (2006) compared the RR Lyrae intrinsic color at minimum light,  $(V - I)_{\min,0}^{\phi(0.5-0.8)}$ , of OGLE bulge RR Lyrae stars, dereddened according to Sumi (2004), with field RR Lyrae colors. They concluded that there is a discrepancy of 0.05–0.08 mag between the RR Lyrae-to-red clump (RC) color differential of the bulge population (measured from OGLE data) and that of the local population. Whether this is a result of a RR Lyrae or RC color discrepancy as a function of environment has substantial implications on the use of absolute magnitudes of RR Lyrae variables. We apply the minimum light RR Lyrae color reddenings to the MACHO bulge RR Lyrae to check if the absolute magnitude of RR Lyrae stars are indeed environment independent.

The structure of this paper is as follows. The observations and data are given in Section 2. The light curves and mean observational properties of the program RR Lyrae variables are presented in Section 3, and comments about individual stars follow in Section 4. A thorough investigation on the use of minimum light colors to calibrate  $E(V - R)$  is presented in Section 5. In Section 6, the intrinsic minimum light colors are

then compared to RR Lyrae variables in the Galactic bulge and anomalous colors of Galactic bulge RR Lyrae are discussed.

## 2. OBSERVATIONS AND REDUCTIONS

Observations were made over 31 nights at the WIYN 0.9 m telescope at Kitt Peak (on seven nights over 2006 May 4–11), and at the 1.3 m McGraw-Hill Telescope at the MDM observatory (on 24 nights from 2006 September 29 to July 2, August 30 to September 7, and from 2008 March 8 to 18). The WIYN Telescope was equipped with the S2KB  $2048 \times 2048$  CCD, giving a field of view  $20.5$  on a side, with a scale of  $0.60$  pixel $^{-1}$ . The  $2048 \times 2048$  Echelle and  $1024 \times 1024$  Templeton CCDs were used on the MDM telescope, giving fields of view of  $17.3$  and  $8.7$  on a side, respectively, with scales of  $0.508$  pixel $^{-1}$ . The observations were obtained primarily in the  $R$  filter, but some  $V$ -band images were also obtained. On each night, twilight and dawn flats were taken in the  $R$  and  $V$  filters. The images were overscan-corrected, trimmed, and bias-subtracted in the normal fashion using standard IRAF tasks.

Landolt (1992) standard stars were observed in the  $R$  and  $V$  bands on three photometric nights, 2006 May 6, May 7, and May 8, with a wide range of color, air mass, and universal time that encompassed the various properties of the program stars. Ten stars in the vicinity of each RR Lyrae variable were selected as comparison stars, which could potentially be used to perform differential photometry on nights that were not photometric. Instrumental magnitudes of the RR Lyrae variable, the comparison stars, and the standard stars were computed from each image using the DAOPHOT task PHOT (Stetson 1994), as implemented in IRAF.

For each photometric night, transformation equations of the form

$$r - R = c_{R,0} + c_{R,1}X_R + c_{R,2}(V - R) \quad (1)$$

and

$$v - V = c_{V,0} + c_{V,1}X_V + c_{V,2}(V - R) \quad (2)$$

were constructed, where  $r$  represents the instrumental magnitude,  $R$  and  $V$  are the standard magnitude from Landolt (1992), and  $X_R$  and  $X_V$  are the air mass in  $R$  and  $V$ , respectively. The coefficients were first obtained using least-squares minimization. The coefficients  $c_{R,2}$ , the  $R$ -band color terms, for all three nights were averaged together to find  $\langle c_{R,2} \rangle$ . The value of  $\langle c_{R,2} \rangle$  is then used as a constant in Equation (1) instead of  $c_{R,2}$ , and the coefficients  $c_{R,0}$  and  $c_{R,1}$  are found again. This procedure was also carried out with the  $V$ -band color terms to find  $\langle c_{V,2} \rangle$ , and to solve for  $c_{V,0}$  and  $c_{V,1}$ .

For the photometric night 2006 May 8, the transformation equation

$$r - R = c_0 + c_1X_R \quad (3)$$

was also used. This is because for that particular photometric night, not many  $V$ -band images of RR Lyrae variables were collected and hence, for a subset of the RR Lyrae variables observed on this night, no  $(V - R)$  information at a particular phase was known. As the color terms found were small,  $\langle c_{R,2} \rangle = -0.022$  and  $\langle c_{V,2} \rangle = -0.011$ , and as the RR Lyrae colors do not vary much, the omission of the color term is small. The rms scatter of the points around each best fit is shown in Table 1. The number of stars used in each fit and the number of standard star fields observed that night are also shown. The rms from Equation (3) with no color term is indicated by  $\text{rms}_{R,nc}$ . The number of calibration images for each RR Lyrae that uses a

**Table 1**  
Photometric Transformations

Night	JD	$N_{fids}$	$rms_R$	$N_R$	$rms_V$	$N_V$	$rms_{R,nc}$
2006 May 6	2453861	6	0.017	38	0.011	40	...
2006 May 7	2453862	7	0.023	50	0.017	47	...
2006 May 8	2453863	6	0.025	37	0.018	32	0.025

**Table 2**  
Individual Photometric Observations

Name	HJD-2,450,000	$R$	$\sigma_R$
UY Boo	3861.8354	10.701	0.015
UY Boo	3862.7655	10.751	0.016
UY Boo	3862.8793	10.885	0.018
UY Boo	3863.6659	10.943	0.017
UY Boo	3863.6879	10.933	0.017
UY Boo	3863.7024	10.949	0.015
UY Boo	3863.7284	10.972	0.016
UY Boo	3863.8846	10.486	0.017

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms in the online journal. A portion is shown here for guidance regarding its form and content.)

color term ( $N_{VR}$ ) and the number of calibrations with no color term ( $N_R$ ) are listed for each star in Table 3.

Once these equations were determined, we applied them to all of the comparison stars. Every variable star field was observed at least twice on at least two different photometric nights. Most variable star fields were observed 4–9 times over the three photometric nights. When averaged together, the magnitudes for each comparison star agreed well, with the dispersion about the mean being less than 0.012 mag in most cases. When performing differential photometry, only comparison stars with dispersions about the mean being less than 0.025 mag were used. On average, each RR Lyrae field had three suitable comparison stars.

Over the course of the data reduction, ACL noticed that the S2KB CCD encountered an excess of light falling near the center of the chip in the flat fields. Thus, a 2%–4% overillumination near the central region of the chip occurred. Using Layden’s aperture mask, correction images were developed that were applied to the data taken using this CCD.

Table 2 presents the photometry thus obtained. The columns contain (1) the Heliocentric Julian Date of midobservation (minus 2,450,000 days), (2) the Johnson  $R$  magnitude, and (3) its error.

### 3. LIGHT CURVES

Almost all of the observed data were folded by the period listed in the General Catalogue of Variable Stars (Kholopov 1985). For the stars SS CVn and AX Leo, the period from Maintz (2005) was used, for UZ CVn the period from Vandenbroere & Berthold (2001) was used, and for IO Lyr and AN Ser, the period from Le Borgne et al. (2007) was used. These periods yielded light curves in which our 2006 data and 2008  $R$ -band data were more closely aligned in phase space. As suggested by previous investigators, all 21 stars pulsate in the fundamental mode, and the stars AB UMa, RV UMa, and SS CVn, exhibit light curve modulation, the so called Blazhko effect. There are other cases of stars with noticeable light curve scatter, namely UY Boo, AX Leo, and BT Dra. UY Boo has been shown by Le Borgne et al. (2007) to have irregular slow variations, and AX Leo

**Table 3**  
Photometric Parameters of Program RR Lyrae Stars

Star	Period (d)	$\langle R \rangle$	$A_R$	$N_{obs}$	$F_{R,order}$	$N_{VR}$	$N_R$
UY Boo <sup>a</sup>	0.6508365	10.76	0.52	70	$F_8$	4	4
TV CrB	0.5846145	11.74	0.98	78	$F_8$	2	3
SS CVn <sup>b</sup>	0.47853	11.73	0.95	36	$F_8$	3	0
UZ CVn	0.69779191	11.90	0.74	105	$F_8$	5	4
BC Dra	0.719576	11.27	0.47	129	$F_6$	1	4
BT Dra	0.588673	11.42	0.64	134	$F_8$	2	2
SW Dra	0.56966993	10.29	0.74	115	$F_8$	2	0
CW Her	0.6238405	12.41	0.87	85	$F_8$	2	3
VZ Her	0.44032789	11.36	1.05	70	$F_8$	1	8
AX Leo <sup>c</sup>	0.726776	12.02	0.46	114	$F_6$	2	0
FN Lyr	0.5273984	12.59	1.00	92	$F_6$	2	4
IO Lyr	0.57712215	11.59	0.78	81	$F_8$	2	4
V413 Oph	0.44900586	11.70	0.95	76	$F_8$	2	1
AN Ser	0.52207162	10.73	0.79	96	$F_8$	2	4
AT Ser	0.746568	11.26	0.70	88	$F_6$	2	3
AW Ser	0.597114344	12.69	0.97	86	$F_8$	2	4
AB UMa <sup>d</sup>	0.599577	10.74	0.36	47	$F_6$	4	5
RV UMa <sup>e</sup>	0.468060	10.64	0.58	84	$F_8$	5	3
AT Vir	0.5257931	11.18	0.95	64	$F_8$	4	3
AV Vir	0.656909	11.56	0.62	84	$F_8$	4	2
ST Vir	0.410820	11.41	0.99	85	$F_8$	2	3

#### Notes.

<sup>a</sup> HJD 4533.7143–4541.9318.

<sup>b</sup> HJD 4538.7370–4543.9270.

<sup>c</sup> HJD 4533.6980–4543.8652.

<sup>d</sup> HJD 4533.8675–4536.8210.

<sup>e</sup> HJD 4533.7283–4543.9340.

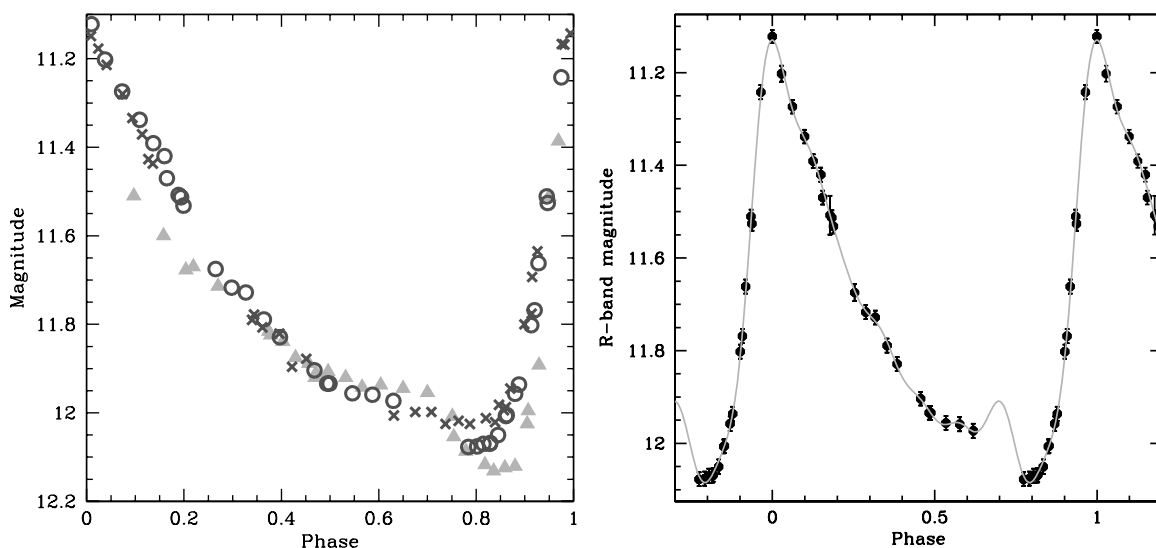
has been reported by Schmidt (2002) to show noticeable light curve scatter. Piersimoni et al. (1993) found that BT Dra has a bump that precedes the light minimum, and possibly, a hump on the rising branch. We see light curve scatter at maximum and minimum light but no hump on the rising branch for BT Dra.

The estimated intensity mean  $R$ -band magnitude and pulsation amplitudes for each star from the observed data are found from a Fourier decomposition of the light curve. The order of the Fourier fit (from a fourth to eighth order) did not change the computed mean magnitude of the star. However, variations of the amplitude, on the order of  $\sim 0.01$  mag, occurred depending on the order of the fit. The error in the  $R$ -band amplitude is hence 0.01 mag. These values are presented in Table 3 along with the number of observed data points for each star,  $N_{obs}$ , and the order of the Fourier fit used to determine the amplitude. For the stars exhibiting scatter in their light curves due to, i.e., the Blazhko effect, a narrow range of HJD is used in determining the stars  $R$ -band magnitude and amplitude. For these cases, the limited HJD range shows no detectable scatter in the light curve, yet there is ample data for an accurate Fourier fit. Individual light curves for two representative stars, one Blazhko star and one normal star, are seen in Figures 1 and 2.

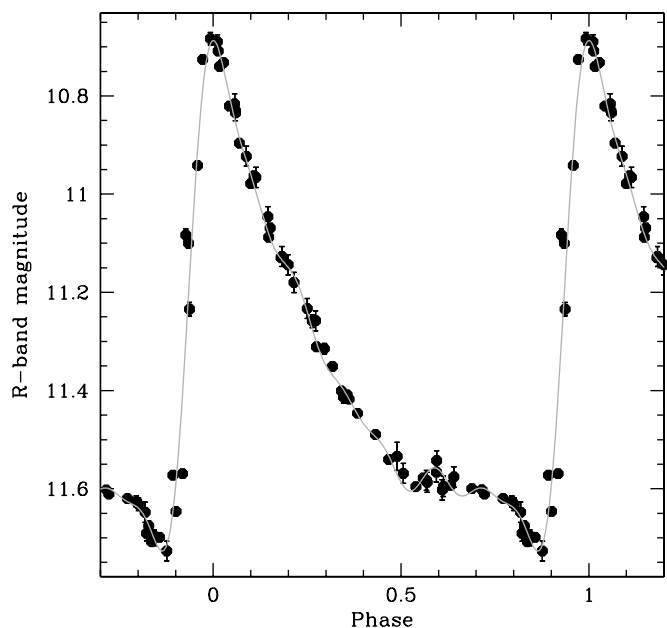
Corresponding  $V$ -band light curves from the literature are found for the program stars. This is so that the  $(V - R)$  at minimum  $V$ -band light,  $(V - R)_{min}$ , can be calculated for each of the program stars. An analysis on the use of  $(V - R)_{min}$  for reddening determination can thus be carried out.

Almost half of the corresponding  $V$ -band light curves in our sample are obtained from the ASAS database (Pojmanski 2002). The ASAS data used cover a range of observations from 2001 to 2009 and for each measurement, five  $V$ -band magnitude values are given which correspond to five different aperture sizes used in the photometry. The time series,  $V(t)$ , was generated by





**Figure 1.** *R*-band light curve of the Blazhko RR Lyrae SS CVn. Left: the triangles represent data taken in 2006; the crosses and circles represent data taken in 2008, at the beginning and end of the run, respectively. Right: *R*-band light curve of SS CVn with the HJD range of 4535.6571–4543.9312 days. Overplotted is the eighth-order Fourier fit to the observed data.



**Figure 2.** *R*-band light curve of the RR Lyrae VZ Her. Overplotted is the eighth-order Fourier fit to the observed data.

weighting the average of the magnitude values given for the five apertures as described by Kovács (2005). The corresponding *V*-band data for our program stars are mentioned in the individual notes for each RR Lyrae star.

The *V* and *R* light curves were fit with a series of six RR Lyrae light curve templates as described in Layden et al. (1996) to find where maximum light occurs and align it with  $\phi = 0$ . For stars with noticeable light curve scatter (that was not due to the Blazhko effect), the light curve was separated into different observing seasons, which usually corresponded to different light curve “branches.” The period for each of these “branches” was solved for, and again aligned with  $\phi = 0$ . Hence, the phaseshift is treated as a free parameter. Since color and reddening are not related to the long-term period stability, this is an acceptable way to reduce light curve scatter, especially when combining photometry from widely differing years.

#### 4. COMMENTS ON INDIVIDUAL STARS

*O*–*C* curves are widely used for investigating the period behavior of variable stars. The *O*–*C* value refers to “observed–calculated:” the difference between the observed and calculated epoch of a light curve. The GEOS RR Lyr Survey (Le Borgne et al. 2007), contains  $\sim 50,000$  times of maximum light from more than 3000 RR Lyr stars obtained either visually or with electronic devices or photographically. From these measurements, *O*–*C* curves are made.

*UY Boo* This star has an *O*–*C* curve that changes by  $\sim 4$  days from approximately HJD 2,420,000 to 2,450,000 days. Le Borgne et al. (2007) showed that UY Boo exhibits irregular slow variation. We note extreme light-curve scatter in the *R*-band data. To find its photometric properties, we use the UY Boo data with the HJD range indicated in Table 3. The *V* band taken for this star is taken from ASAS. To find  $(V - R)_{\min}$ , separate results are presented for the 2006 and 2008 data to describe the star’s behavior at these distinct points in its irregular variation.

*TV CrB*. This star is shown to have a well-defined linearly increasing period (Le Borgne et al. 2007). It has an *O*–*C* curve that changes in a relatively linear manner by  $\sim 0.2$  days from approximately HJD 2,410,000 to 2,450,000 days. We see no light curve scatter in the *R* band between the 2006 and 2008 data. The *V*-band data are taken from both the Behlen Survey and A. Layden et al. (2010, in preparation).

*SS CVn*. This star exhibits the Blazhko effect with a Blazhko period of 97 days (Wils et al. 2006). Similarly, we find that the 2006 and 2008 *R*-band data do not match up well with each other. As there is no *V*-band data with approximately the same HJD range as the *R*-band data in the literature, no  $(V - R)_{\min}$  was found for this star.

*UZ CVn*. This star has an *O*–*C* curve that is shown to be represented either by an abrupt period change around epoch 28,000 or by a parabolic fit (Vandenbroere & Berthold 2001). From approximately HJD 2,430,000 to 2,450,000 days, the *O*–*C* curve changes by  $\sim 0.4$  days. We see no evidence of light curve variation in our 2006 and 2008 data. The *R*-band data used are from the Behlen Survey combined with the new observations presented in this paper. The *V*-band is taken from

Behlen Variable Star Survey. We find that the period given by Vandenbroere & Berthold (2001), 0.69779191 days, yields not only a more tightly phased light curve in the Behlen data, but also results in a better fit between the  $R$ -band Behlen data and the data presented here.

*BC Dra.* The  $V$ -band photometry is taken from Szabados & Stobie (1982), with a mean  $V$  error of 0.036 mag.

*BT Dra.* This star has an  $O-C$  curve with a roughly linear trend in decreasing  $O-C$ , with a 0.1 day variation from approximately HJD 2,420,000 to 2,450,000 days. The  $V$ -band data are taken from Piersimoni et al. (1993) who note that the light curve of BT Dra has a bump that precedes minimum light, and possibly, a bump on the rising branch. We find scatter in the  $R$ -band data of  $\sim 0.05$  mag at maximum and minimum light. This is not seen for the rest of the light curve.

*SW Dra.* This star has a significant phase lag between light and radial velocity curves, and its  $O-C$  curve shows a gradual increase from approximately HJD 2,440,000 to 2,455,000 days. The  $V$ -band data are taken from both Stiepen (1972) and Jones et al. (1987). Due to few bright stars in its vicinity, only one comparison star was suitable to use for the  $R$ -band light curve.

*CW Her.* This stars'  $O-C$  curve changes by  $\sim 0.2$  days from approximately HJD 2,440,000 to 2,450,000 days. The  $V$ -band light curve is taken from the Behlen Variable Star Survey.

*VZ Her.* This star changes its period (Szeidl et al. 1986). These  $V$ -band data are from Fitch et al. (1966) and Sturch (1966).

*AX Leo.* This star shows noticeable light curve scatter (Schmidt 2002). From our  $R$ -band observations we find a 0.03 mag discrepancy at some points in the light curve between the 2006 and 2008 data. The  $V$ - and  $R$ -band light curves are taken from the Behlen Survey and only data from 1990 are used. The data from the Behlen Survey taken after 1990 are too sparse to accurately determine its properties.

*FN Lyr.* This star has the largest  $E(B-V)$  value in the sample, and hence it is the most uncertain. This star was not used in the calibration of  $(V-R)_{\min,0}$ .

*IO Lyr.* The  $V$ -band data from Stiepen (1972) and Sturch (1966) have sparse phase coverage at minimum light (two data points). Hence these data are combined with the  $V$ -band data from A. Layden et al. (2010, in preparation). No significant difference in  $(V-R)_{\min}$  is found when using only the Stiepen (1972) and Sturch (1966) data, or when using the A. Layden et al. (2010, in preparation) data.

*AN Ser.* The  $V$ -band light curve is taken from ASAS. The  $V$ -band photometry taken by Lub (1977) and transformed to Johnson  $V$  agrees very well with the more current ASAS photometry, although they are taken more than almost 40 years apart.

*AT Ser.* This star has an  $O-C$  curve that changes by  $\sim -0.6$  days from approximately HJD 2,418,000 to 2,455,000 days. It then seems to hover around zero. There is no noticeable light curve discrepancies between the 2006 and 2008  $R$ -band data. The  $V$  band is taken from ASAS Project.

*AW Ser.* The  $V$ -band data from ASAS project have a lot of scatter, especially at minimum light. This could be due to its relatively faint magnitude. Its  $O-C$  curve has only nine points, but does show a change by  $\sim 0.2$  days from approximately HJD 2,448,000 to 2,455,000 days. We do not see any difference in the  $R$ -band 2006 and 2008 data. The data from A. Layden et al. (2010, in preparation) corresponds very well with the ASAS data, but show significantly less light curve scatter. Hence, the Layden data are used.

*AB UMa.* This star exhibits the Blazhko effect, and hence there is a significant discrepancy in the  $R$ -band 2006 and 2008

light curve data. In the determination of  $(V-R)_{\min}$ , both the  $V$ - and  $R$ -band data from the Behlen Survey is used, which is taken simultaneously, to avoid inconsistencies in the light curve due to different cycles in the Blazhko light curve. Two separate results are presented to describe the star's behavior at these distinct points in its Blazhko phase.

*RV UMa.* This star exhibits the Blazhko effect with a Blazhko period of 93 days (Wils et al. 2006). A thorough light curve analysis of RV UMa by Hurta et al. (2008) reveals the quintuplet frequency solution of this star. The  $R$ -band data show clearly a discrepancy in the 2006 and 2008 data. No  $V$ -band data with the same HJD range as that of the  $R$ -band were found, and so no  $(V-R)_{\min}$  was found for this star.

*AT Vir.* This star is shown to have a linearly decreasing period (Le Borgne et al. 2007). It shows a parabolic shape in its  $O-C$  diagram, varying by  $-0.4$  days from approximately HJD 2,420,000 to 2,450,000 days. We do not find any  $R$ -band light curve scatter between the 2006 and 2008 data, although admittedly, there is not a wealth of  $R$ -band data for this star. The  $V$ -band is taken from ASAS Project.

*AV Vir.* The  $V$ -band light curve is taken from the ASAS Project.

*ST Vir.* Le Borgne et al. (2007) find that the  $O-C$  pattern for this star shows evidence for several changes in the direction of the period variation. We do not see any scatter in our 2006 and 2008  $R$ -band data. The  $V$ -band data are taken from both the ASAS Project.

## 5. REDDENING CALIBRATION

The apparent  $(V-R)$  colors of the program stars are found at minimum  $V$ -band light by (1) performing a Fourier decomposition on the  $V$ - and  $R$ -band light curves and finding the minimum  $(V-R)$  at minimum  $V$ -band light,  $(V-R)_{\min}^F$ , and (2) finding the average color for phases between 0.5 and 0.8,  $(V-R)_{\min}^{\phi(0.5-0.8)}$ . Kunder et al. (2008) noticed a slight correlation between amplitude and  $(V-R)_{\min,0}^{\phi(0.5-0.8)}$ . However, to obtain  $(V-R)_{\min}^F$ , a Fourier decomposition is performed which requires a relatively complete light curve, especially at minimum light. We investigate these two methods further to assess how well the apparent  $(V-R)$  colors of RR Lyrae stars can be used to find the interstellar reddening along the line of sight to the star.

When fitting a Fourier decomposition to the  $V$ - and  $R$ -band data, the same fit order for the  $R$  band listed in Table 3 is used; the fit order for the  $V$  band is given in Table 4. In general, an eighth-order fit was used for both the  $V$ - and  $R$ -band light curves. The apparent  $(V-R)$  color at minimum  $V$ -band light,  $(V-R)_{\min}^F$ , is dereddened from the reddening values taken from Schlegel et al. (1998). The adopted  $E(V-R)$  values are shown in Table 4, as well as the computed intrinsic color at minimum  $V$ -band light,  $(V-R)_{\min,0}^F$  (Column 7) and the error in the color at minimum  $V$ -band light,  $\sigma(V-R)_{\min,0}^F$ . The  $V$ -band amplitudes, as determined from the  $V$ -band Fourier fits, are also shown.

To estimate an error in  $(V-R)_{\min}^F$  value for our program RR Lyrae stars, various tests are performed to assess how much  $(V-R)_{\min}^F$  changes. First, a few points in the  $V$  and  $R$  light curves were removed, particularly those points close to minimum  $V$ -band light. A Fourier decomposition was applied again to these modified light curves, and  $(V-R)_{\min}^F$  was re-calculated. The  $(V-R)_{\min}^F$  changed by  $\sim 0.005$  mag. This indicates that the determination of  $(V-R)_{\min}^F$  is largely independent

**Table 4**  
Minimum Light Colors at Minimum V-band Light for Field RR0 Lyrae Stars

Star	$E(B - V)$	$E(V - R)$	$A_V$	[Fe/H]	$\Delta \log P$	$(V - R)_{\min,0}^F$	$\sigma(V - R)_{\min}^F$	$F_{V,\text{order}}$	$(V - R)_{\min,0}^{\phi(0.5-0.8)}$	$N_{\min,V}$	$N_{\min,R}$
TZ Aur	0.064	0.051	1.33	-0.79	0.18	0.25	0.01	$F_8$	$0.238 \pm 0.005$	227	227
UY Boo	0.037	0.030	0.79	-2.56	0.03	0.28	0.02	$F_4$	$0.295 \pm 0.018$	15	4
UY Boo	0.037	0.030	0.79	-2.56	0.03	0.30	0.02	$F_8$	$0.300 \pm 0.011$	16	24
AL CMi	0.030	0.024	0.72	-0.79	0.15	0.32	0.01	$F_8$	$0.323 \pm 0.031$	13	13
TV CrB	0.040	0.032	1.34	-2.33	0.03	0.28	0.015	$F_8$	$0.251 \pm 0.006$	60	12
UZ CVn	0.024	0.019	0.85	-1.89	-0.01	0.28	0.01	$F_4$	$0.282 \pm 0.025$	4	20
BC Dra	0.069	0.055	0.59	-2.00	0.01	0.26	0.01	$F_8$	$0.273 \pm 0.030$	16	28
BT Dra	0.010	0.008	0.78	-1.75	0.10	0.25	0.015	$F_8$	$0.241 \pm 0.007$	42	42
SW Dra	0.015	0.012	0.91	-1.12	0.09	0.27	0.02	$F_8$	$0.263 \pm 0.015$	17	26
CW Her	0.022	0.018	1.07	-2.03	0.00	0.25	0.01	$F_4$	$0.272 \pm 0.007$	5	23
VZ Her	0.031	0.025	1.31	-1.02	0.13	0.27	0.03	$F_8$	$0.283 \pm 0.007$	9	17
GO Hya	0.048	0.038	0.54	-0.77	0.10	0.33	0.01	$F_4$	$0.251 \pm 0.030$	5	5
AX Leo	0.037	0.030	0.63	-1.72	-0.01	0.28	0.01	$F_4$	$0.282 \pm 0.046$	3	3
IO Lyr	0.067	0.054	0.98	-1.14	0.07	0.33	0.01	$F_8$	$0.235 \pm 0.027$	2	17
AN Ser	0.042	0.034	1.01	-0.07	0.12	0.29	0.01	$F_8$	$0.273 \pm 0.030$	36	32
AT Ser	0.039	0.031	0.87	-2.03	-0.08	0.30	0.01	$F_8$	$0.266 \pm 0.025$	68	25
AW Ser	0.039	0.031	1.20	-1.67	0.00	0.25	0.01	$F_8$	$0.257 \pm 0.011$	36	21
AB UMa	0.027	0.022	0.39	-0.49	0.17	0.28	0.02	$F_4$	$0.249 \pm 0.032$	3	3
AB UMa	0.027	0.022	0.39	-0.49	0.17	0.29	0.02	$F_4$	$0.305 \pm 0.031$	4	4
AT Vir	0.031	0.025	1.14	-1.60	0.08	0.29	0.01	$F_8$	$0.278 \pm 0.010$	35	8
AV Vir	0.032	0.026	0.72	-1.25	0.04	0.29	0.01	$F_8$	$0.260 \pm 0.017$	47	24
ST Vir	0.041	0.033	1.31	-0.67	0.16	0.29	0.01	$F_8$	$0.256 \pm 0.015$	48	20

on the inclusion or exclusion of a few data points in the light curve. This is most likely due to the fact that most of the light curves presented here are quite complete. There are some stars with not many points in their light curves, e.g., UY Boo, and the adopted for  $(V - R)_{\min}^F$  is larger for these stars.

Second, different fit orders are employed. In this case, the  $(V - R)_{\min}^F$  value can change by  $\sim 0.02$  mag. All fits are examined by eye to see which Fourier fit approximates the light curve best, especially the fit at minimum V-band light. From these two tests, an error of 0.01 mag in  $(V - R)_{\min}^F$  is estimated. Stars with either noisy or sparse light curves have larger adopted errors. The error in  $E(V - R)$  is also about 0.01 mag. Hence, most of the adopted errors in our  $(V - R)_{\min,0}^F$  values is 0.01 mag. The error in  $(V - R)_{\min,0}^F$  is given in Table 4.

The zero-point error in the R-band light curve influences both  $(V - R)_{\min}^F$  and  $(V - R)_{\min,0}^{\phi(0.5-0.8)}$ . This varies from star to star, depending mainly on the sigma in the calibrated magnitude of the comparison stars and the number observations of the comparison star. In general, a comparison star has a sigma in the calibrated magnitude that is less than 0.021 mag, and most have a smaller sigma ( $\sim 0.012$  mag). Also, in general each field was observed photometrically 3 or more times which results in a zero-point error that is 0.010 mag or less. The two RR Lyrae fields with SW Dra and AX Leo have only two calibration observations, and have slightly larger zero-point uncertainties of  $\sim 0.018$  mag and  $\sim 0.011$  mag, respectively. The zero-point error is taken into account when calculating the error in the individual light curve data points presented in Table 2 and when performing the Fourier decomposition to the light curve.

Computing the colors at minimum light via an arithmetic mean of the observed  $(V - R)$  data having phases between 0.5 and 0.8 is relatively straight forward. The mean values, in magnitude units, their standard errors of the mean, and the number of points at minimum light in the V and R light curves are reported in the last three columns of Table 4.

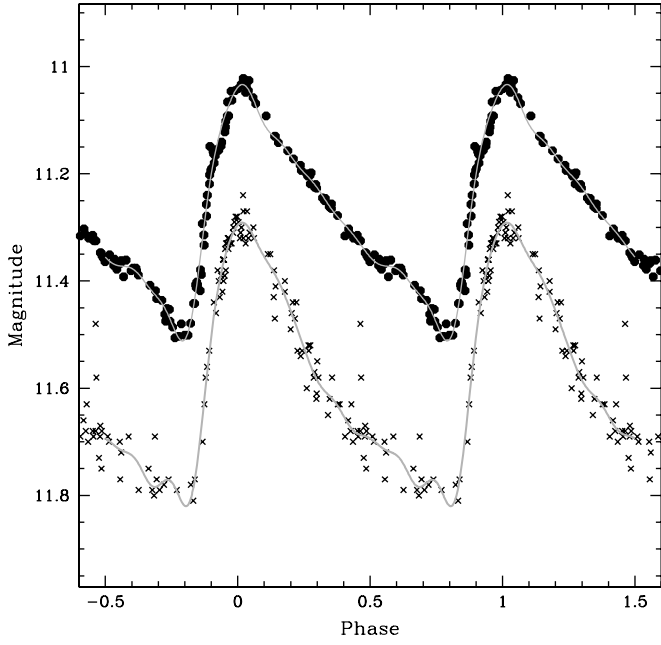
Three additional stars not observed in our project are included in Table 4 and in our subsequent analysis. The two stars, AL

CMi and GO Hya, have photometry from the Behlen Variable Star Survey (Schmidt 1991, 1995) and not only have adequate phase coverage for a good estimate of  $(V - R)_{\min}$ , but also well-known reddening values. The third star not observed in our project is TZ Aur, and the photometry is taken from Warner (2008).

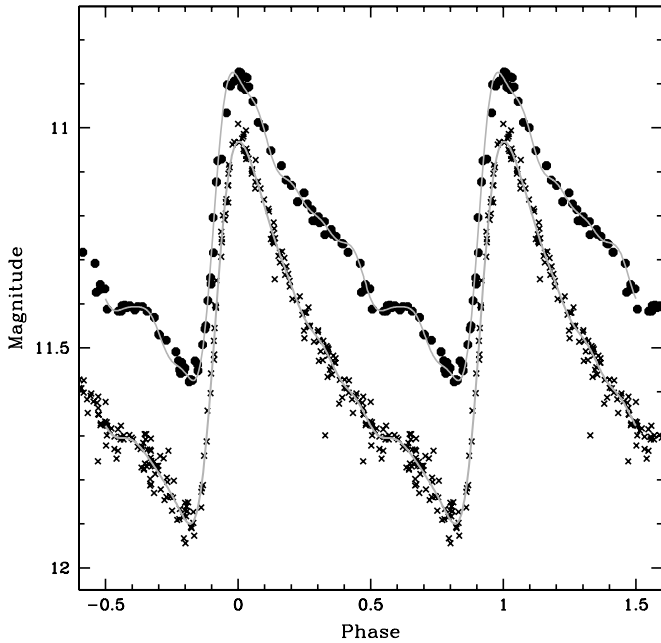
For three stars observed from our program, (AB UMa, AX Leo, CW Her) photometry from the Behlen Survey was used exclusively in determining  $(V - R)_{\min}$ . This is because these stars had light curves that exhibited light curve variation as a function of Julian Date, and none of these stars had V-band data with the same HJD as that of the R-band data presented here. The Behlen Survey data have the advantage that V and R band are taken simultaneously. The scatter in light curve due to the intrinsic properties of the star, i.e., Blazhko effect, irregular slow variations, etc., is exhibited identically the light curves for both passbands. For these stars in which the V- and R-band light curves were taken simultaneously, an error of 0.01 mag in  $(V - R)_{\min,0}^F$  is assigned. For the star UZ CVn, the R-band data from the Behlen Variable Star Survey are supplemented with that from this paper. The combined V- and R- band photometry used to determine  $(V - R)_{\min}$  is shown for two representative stars in Figures 3 and 4.

When performing a Fourier decomposition on the V- and R-band light curves and finding the  $(V - R)$  at minimum V-band light, the mean  $(V - R)_{\min,0}^F$  is  $0.28 \pm 0.02$  mag, where 0.02 is the dispersion about the mean. Finding the average  $(V - R)$  color for phases between 0.5 and 0.8 results in a mean  $(V - R)_{\min,0}^{\phi(0.5-0.8)}$  of  $0.27 \pm 0.02$  mag. These results are within the error bars of each other.

Figures 5 and 6 show the intrinsic color at minimum V-band light,  $(V - R)_{\min,0}^{\phi(0.5-0.8)}$ , as a function of period, [Fe/H], V-band amplitude, and  $\Delta \log P$ . There is not much difference when using  $(V - R)_{\min,0}^F$ . The period shift,  $\Delta \log P$ , is the difference between the periods of RR Lyrae variables at fixed amplitude. An RR Lyrae amplitude is usually considered to be a function of temperature (see Clement & Shelton 1999; Kunder & Chaboyer



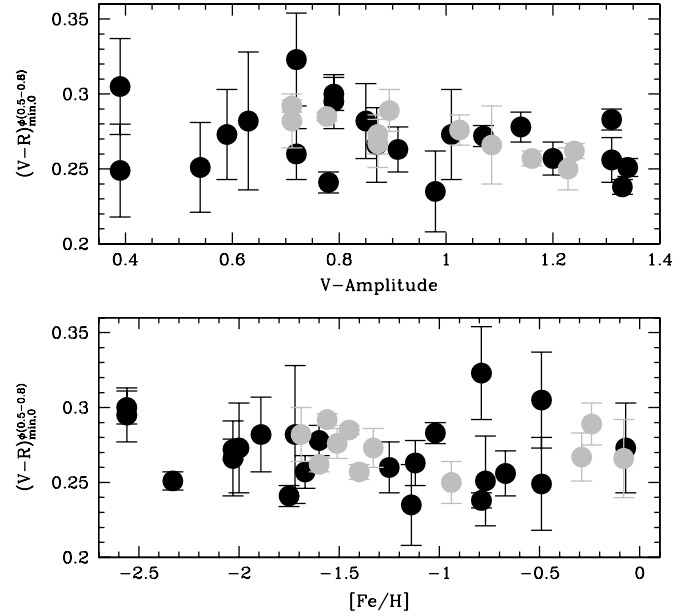
**Figure 3.** V- and R-band light curves of the RR Lyrae star BC Dra. The circles are from the R-band observations presented here, and the crosses are from V-band observations from Szabados & Stobie (1982). The solid lines designate an eighth-order Fourier fit to the observed data.



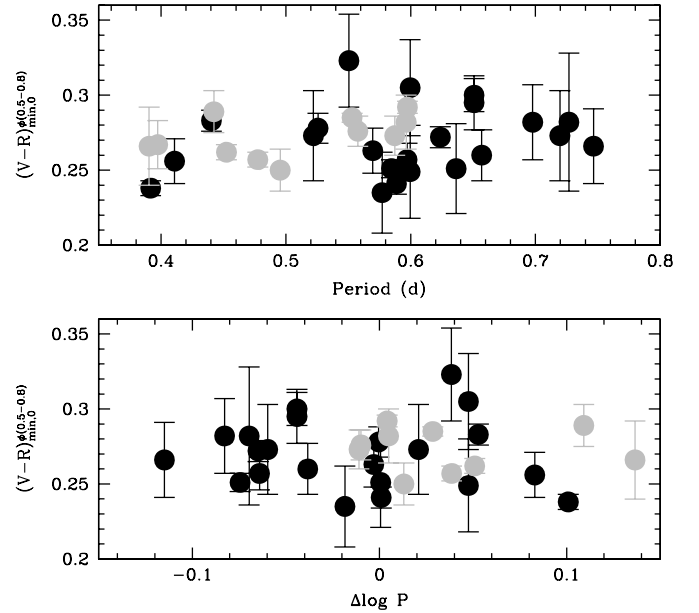
**Figure 4.** V- and R-band light curves of the RR Lyrae star AT Ser. The symbols are as in Figure 3, only the V-band data are taken from the ASAS Project.

2009). This comparison is usually made between the RR0 Lyrae stars in different globular clusters (Sandage 1981; Carney et al. 1992; Sandage 1993), and is thought to indicate the evolutionary state of an RR Lyrae variable.

The mean  $(V-R)_{\min,0}^{\phi(0.5-0.8)}$  is independent or at least very insensitive to metallicity, amplitude, and  $\Delta \log P$ . No trend is seen in a least squares analysis of  $(V-R)_{\min,0}^{\phi(0.5-0.8)}$  as a function of  $[\text{Fe}/\text{H}]$ ,  $\Delta \log P$ , period, or  $V$  amplitude. Weighted least square fits led to slopes of  $+0.02 \pm 0.04 \text{ mag d}^{-1}$  (for period),  $-0.023 \pm 0.014$  (for  $V$  amplitude),  $+0.016 \pm 0.05 \text{ mag dex}^{-1}$  (for  $[\text{Fe}/\text{H}]$ ), and  $+0.026 \pm 0.02 \text{ mag d}^{-1}$  (for  $\Delta \log P$ ). These



**Figure 5.** Minimum  $(V-R)$  color,  $(V-R)_{\min,0}^{\phi(0.5-0.8)}$ , is shown as a function of  $[\text{Fe}/\text{H}]$  and  $V$  amplitude. The gray circles represent stars previously analyzed by Kunder et al. (2008).



**Figure 6.** Minimum  $(V-R)$  color,  $(V-R)_{\min,0}^{\phi(0.5-0.8)}$ , is shown as a function of period and  $\Delta \log P$ . Symbols are the same as in Figure 5.

results are very similar for  $(V-R)_{\min,0}^F$ , when finding the  $(V-R)$  at minimum  $V$ -band light from a Fourier decomposition. Weighted least square fits led to slopes of  $+0.07 \pm 0.04 \text{ mag d}^{-1}$  (for period),  $-0.031 \pm 0.012$  (for  $V$  amplitude),  $+0.002 \pm 0.005 \text{ mag dex}^{-1}$  (for  $[\text{Fe}/\text{H}]$ ), and  $+0.0003 \pm 0.06 \text{ mag d}^{-1}$  (for  $\Delta \log P$ ).

The greatest evidence of an  $(V-R)_{\min,0}$  dependence is with  $V$  amplitude, where a  $2\sigma$  slope in the  $(V-R)_{\min,0}$  versus  $V$ -amplitude plane is found. This is the case for both methods of finding minimum light. Although in both cases the slope with  $V$  amplitude is insignificant, the slope with  $(V-R)_{\min,0}^F$  is larger, in contrast with the finding of Kunder et al. (2008). The larger



sample size shows that both methods for determining minimum light are independent on  $V$  amplitude.

Of particular interest is the relation of  $(V - R)_{\min,0}$  with  $[\text{Fe}/\text{H}]$ . Guldenschuh et al. (2005) did not find a trend with minimum light  $(V - I)$  color and  $[\text{Fe}/\text{H}]$ , and no trend is seen with this larger of sample of stars either. It is interesting to note an increase of scatter in  $(V - R)_{\min,0}$  in the more metal-rich stars. This is evident in the Blanco (1992) sample as well and may be absent in the  $(V - I)_{\min,0}$  sample due to the much smaller sample size.

If we seek a multidimensional fit of  $(V - R)_{\min,0}$  with period,  $[\text{Fe}/\text{H}]$ ,  $[\text{Fe}/\text{H}]^2$ , we obtain

$$(V - R)_{\min,0}^{\phi(0.5-0.8)} = (0.21 \pm 0.02) + (0.07 \pm 0.04) P - (0.048 \pm 0.016) [\text{Fe}/\text{H}] - (0.02 \pm 0.01) [\text{Fe}/\text{H}]^2 \quad (4)$$

and

$$(V - R)_{\min,0}^F = (0.27 \pm 0.02) - (0.01 \pm 0.05) P - (0.01 \pm 0.02) [\text{Fe}/\text{H}] + (0.001 \pm 0.008) [\text{Fe}/\text{H}]^2 \quad (5)$$

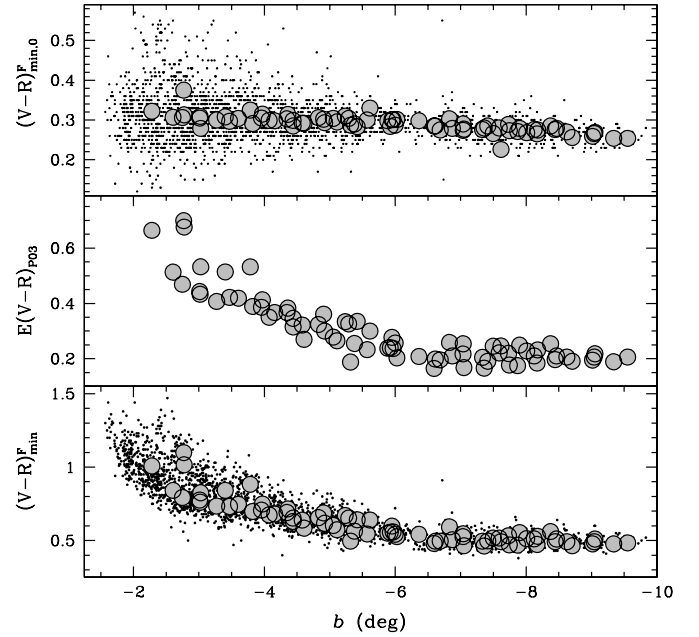
with an rms of 0.022 mag and 0.024 mag, respectively. None of these slopes are formally significant, although Blanco (1992) determined  $E(B - V)$  using these parameters. That the  $(V - R)_{\min,0}^F$  is largely independent on period, amplitude, and  $[\text{Fe}/\text{H}]$  is the same conclusion reached by Kunder et al. (2008), but the result here is based on 31 RR0 Lyrae stars, as opposed to 11.

## 6. ARE THE COLORS OF GALACTIC BULGE RR LYRAE ANOMALOUS?

Stutz et al. (1999) found that the  $(V - I)_0$  colors of the bulge RR Lyrae stars behave in an anomalous way, distinct from the  $(V - I)_0$  colors of local stars. For a fixed period, the Baade's window RR Lyrae stars are  $\sim 0.17$  mag redder in  $(V - I)_0$  than the local RR Lyrae stars. Popowski (2000) showed that part of these offsets were due to errors in the original photometry used. The other part, however, is unclear and various attempts to explain such an offset are reviewed by Popowski (2000). Paczyński & Stanek (1998) and Stutz et al. (1999) explained this offset in terms of a difference between the intrinsic properties of the RC and RR Lyrae stars in the two populations. Popowski (2000) noted that a non-standard interstellar extinction of  $R_V = 2.1$ , rather than the standard value of 2.5, would cause the  $(V - I)_0$  discrepancy between bulge and local RR Lyrae disappear.

Recently, Collinge et al. (2006) found a discrepancy of 0.05 mag between the mean value of  $(V - I)_{\min,0}$  in the OGLE RR Lyrae sample in the Galactic bulge and in the field RR0 Lyrae value obtained by Guldenschuh et al. (2005). The reddening values used in determining OGLE RR Lyrae  $(V - I)_{\min,0}$  was taken from the reddening map from Sumi (2004), which in turn uses the observed color of the RC giants as a measure of reddening. There are three possible causes for this discrepancy.

1. The  $E(V - I)$  values reported by Sumi (2004) are 0.05–0.08 mag too large, most likely caused by a discrepancy between the RR Lyrae-to-RC color differential of the bulge population (measured from the OGLE data) and that of the local population.
2. The Guldenschuh et al. (2005) result is calibrated incorrectly by 0.05–0.08 mag. Their result is based on 16 calibrating stars.

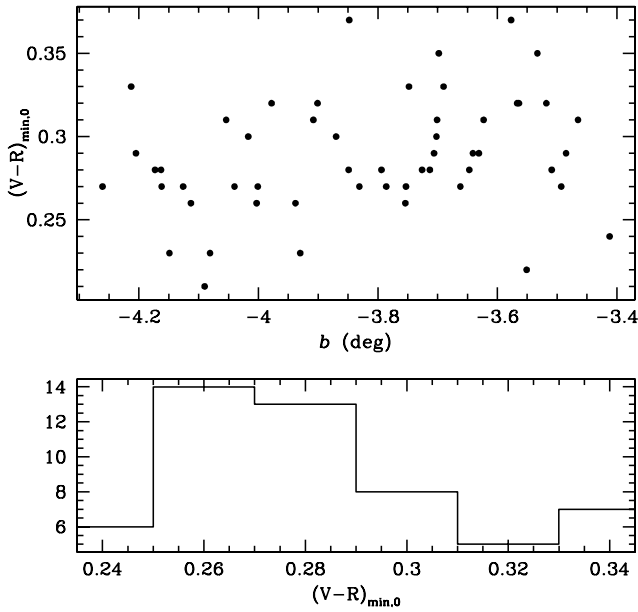


**Figure 7.** Bottom: the binned  $(V - R)$  color at minimum  $V$ -band light of each MACHO field as a function of Galactic  $b$ . The individual minimum light colors of the RR Lyrae are represented by the small black dots. Middle: the average color excess,  $E(V - R)$ , from P03 binned by MACHO field as a function of Galactic  $b$ . Top: the average intrinsic color at minimum  $V$ -band light of each MACHO field, dereddened according to P03, as a function of Galactic  $b$ .

3. The intrinsic colors of RR Lyrae at minimum light are a function of environment. If this were the case, there should be significant doubts on the validity of using RR Lyrae stars as distance indicators. The suggestion of an RR Lyrae intrinsic color discrepancy between the bulge and the local region of the Galaxy has been made before (Stutz et al. 1999; Popowski 2000). An age discrepancy between RR Lyrae in the bulge and in the field could perhaps be the source of such an intrinsic color discrepancy, such as seen in the RC stars (Udalski 1998; Girardi & Salaris 2001). It may be that population effects are more important for the RC than for the RR Lyrae, but further studies of local RR Lyrae colors are needed before this can become a strong statement.

We take a thorough look at this possibility, if the intrinsic colors of RR Lyrae at minimum light are a function of environment. The RR0 Lyrae stars from the MACHO Project (Kunder & Chaboyer 2008) are used for this purpose. As the MACHO light curves have a wealth of data points and good phase coverage, the  $(V - R)$  at minimum light  $V$ -band light from the Fourier decomposition is used to find  $(V - R)_{\min}$ .

In the bottom panel of Figure 7, the average  $(V - R)$  color at minimum  $V$ -band light,  $(V - R)_{\min}^F$ , of each MACHO field is plotted as a function of  $b$ . The middle panel shows the average color excess as determined by Popowski et al. (2003) (hereafter P03),  $E(V - R)_{P03}$ , as a function of Galactic  $b$ . The P03 color excess values are based on the mean colors of stars from the MACHO survey toward the Galactic bulge,  $\langle V - R \rangle$ , in  $4' \times 4'$  regions of the sky. They show that  $\langle V - R \rangle$  can be converted to extinction and visual extinction for 9717 elements at a resolution of about  $4'$  is determined. The conversion from the P03  $\langle V - R \rangle$  to  $E(V - R)_{P03}$  used here is based on an exponential dusty disk model of the Galactic disk which is shown to correspond well with the  $A_V$  reddening map from Stanek (1996). This is in



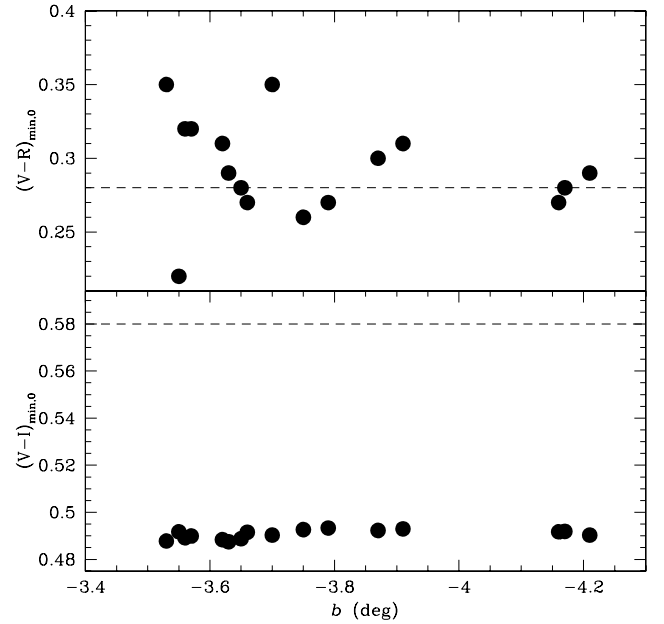
**Figure 8.** Top: the 53 MACHO RR0 Lyrae stars in Baade's Window with well-determined minimum light colors, dereddened according to P03, and plotted against Galactic  $b$ . Bottom: the histogram of  $(V-R)_{\min,0}$  for 53 BW MACHO RR0 Lyrae stars, binned in 0.02 mag bins.

contrast to using the conversion based on the Dutra et al. (2003) reddening map, derived from Two Micron All Sky Survey data in the  $J$ ,  $H$ , and  $K$  bands. The Stanek (1996) reddening map is not only in a passband that does not require additional conversions for the purposes used here, but also has a zero point that has been accurately measured with two independent types of stars (Alcock et al. 1998; Gould et al. 1998).

The top panel of Figure 7 shows the intrinsic  $(V-R)$  color at minimum  $V$ -band light,  $(V-R)_{\min,0}^F$ , as a function of  $b$ . There is a clear trend between  $(V-R)_{\min,0}^F$  and Galactic  $b$ , with a slope of  $0.008 \pm 0.0008 \text{ mag deg}^{-1}$ . This plot illustrates the difficulty of making an accurate analysis using stars in the bulge. Kunder & Chaboyer (2008) used 2435 RR0 Lyrae stars from the MACHO Galactic bulge fields to investigate the structure of the Galactic bulge. They find no significant trends with metallicity, period, or amplitude as a function of position. Hence, there is no physical reason why  $(V-R)_{\min,0}^F$  would be a function of Galactic  $b$ .

The chances of an RR Lyrae being blended increase closer to the Galactic plane, but this does not appear to be a contributing factor in the  $(V-R)_{\min,0}^F$ –Galactic  $b$  trend. Popowski et al. (2005) found evidence for blending for one event out of 53, ( $\sim 2\%$ ) at  $b > -4$  in an analysis of MACHO RC stars to determine to what degree the clump microlensing events are blended. As clump giants have an average absolute  $V$  magnitude that is  $\sim 0.5$  mag fainter than RR Lyrae stars, we would expect blending to be even less of a problem for the RR Lyrae.

The P03 reddening values are based on the CMD of  $4' \times 4'$  regions of the sky. However, it is now known that there is a change in the CMD toward the plane. From  $\sim 700$  giant stars, Zoccali et al. (2008) found that there is a metallicity gradient of  $-0.25$  dex from  $b = -12^\circ$  to  $b = -4^\circ$ . Using isochrones, we find that a 0.25 dex change in metallicity corresponds to a change in color on the RGB of 0.06 mag. The average difference in  $E(V-R)$  between the RR Lyrae and P03 from  $b = -10^\circ$  to  $b = -4^\circ$  is  $\sim -0.04$  mag, and extrapolating this result to cover  $b = -12^\circ$  to  $b = -4^\circ$ , the difference in color excess is  $-0.053$  mag.



**Figure 9.** Top: 16 MACHO bulge RR0 Lyrae star  $(V-R)_{\min,0}$  values, dereddened according to P03. The dotted line represents the value of the local  $(V-R)_{\min,0}$  value, determined in this paper. Bottom: the same 16 OGLE bulge RR0 Lyrae star  $(V-I)_{\min,0}$  values, dereddened according to Sumi (2004). The dotted line represents the value of the local  $(V-I)_{\min,0}$  value, determined by Guldenschuh et al. (2005).

The individual RR Lyrae  $(V-R)_{\min,0}^F$  values are overplotted in the top and bottom panels of Figure 7. It is clear that the dispersion in the RR Lyrae colors increases closer to the Galactic plane (lower  $|b|$  values). The closer to the plane, the larger the differential reddening in one of the P03  $4' \times 4'$  areas. Since the individual RR Lyrae fall at random places within each of P03 reddening map pixel, it is expected that the dispersion of the individual RR Lyrae (top and bottom panels) would increase. As blended RR Lyrae would appear redder, this would also explain why there are some ultra-blue RR Lyrae as well as very red ones. We hence caution the reader that the P03 reddenings have a Galactic  $b$  dependence and can underestimate the amount of color excess,  $E(V-R)$ , in low Galactic  $b$  regions by  $\sim 0.04$  mag.

Baade's window centered on  $(l, b) = (1^\circ, -3^\circ 9')$  and is a region known to have relatively low amounts of interstellar extinction. We turn our analysis to this region. In the top plot of Figure 8, the 53 RR0 Lyrae stars in Baade's Window are shown as a function of Galactic  $b$ . The histogram of  $(V-R)_{\min,0}$  values is shown in the bottom plot. The median of the distribution is 0.28 identical to that of the  $(V-R)_{\min,0}$  found by the local RR Lyrae stars. Their average  $(V-R)_{\min,0}$  is 0.288 mag, and the mode is 0.27 mag.

There are 17 RR0 Lyrae stars in Baade's Window that have OGLE  $(V-I)_{\min,0}$  values from Collinge et al. (2006) that can be matched with a MACHO RR0 Lyrae star. In Figure 9, these stars are shown as a function of Galactic  $b$ . The dotted line indicates the local RR Lyrae  $(V-R)_{\min,0}$  and  $(V-I)_{\min,0}$  value, from the  $(V-R)_{\min,0}$  found above and from the Guldenschuh et al. (2005) value, respectively. The bulge RR0 Lyrae  $(V-R)_{\min,0}$  values are similar to the local RR0 Lyrae value. This is not the case for the intrinsic bulge RR Lyrae minimum light colors and local RR Lyrae  $(V-I)_{\min,0}$  colors.

From the above analysis, the  $(V-R)_{\min,0}$  colors of the bulge RR Lyrae stars behave in a similar manner as local stars. Therefore, we find that it is unlikely that the  $(V-I)_{\min,0}$  colors

of the bulge RR Lyrae behave in an anomalous way from the local RR Lyrae stars. This indicates that there either is a problem with the zero-point accuracy of the Sumi (2004) reddening map, or with the Guldenschuh et al. (2005)  $(V - I)_{\min,0}$  calibration. Given the difficulty of determining reddening in the Galactic bulge, we argue the most likely cause of this is a RR Lyrae-to-RC color differential of the bulge population (measured from the OGLE data). Since we find that the bulge RR Lyrae stars do not exhibit anomalous colors, the most likely explanation seems to be the influence of metallicity on the color of the RC. Unfortunately, systematic errors in the OGLE photometry may appear at approximately the level as the 0.05 mag discrepancy between the mean value of  $(V - I)_{\min,0}$  in the OGLE bulge and the local RR Lyrae sample (Collinge et al. 2006). Hence, the dependence of the color of the RC on metallicity is complicated and would require a thorough look at the OGLE photometry, which is beyond the scope of this paper.

## 7. CONCLUSION

New  $R$ -band photometry for 21 local RR0 Lyrae stars is presented. The  $R$ -band light curves have between 65 and 145 data points per star. Seventeen of these light curves are combined with  $V$ -band light curves from the literature, and the  $(V - R)$  color at minimum light is found. Fourteen additional stars from the literature are added to our sample.

Two definitions of  $(V - R)_{\min}$  are explored.  $(V - R)_{\min}^F$  is defined as the minimum light color at minimum  $V$ -band light found by performing a Fourier decomposition to the  $V$  and  $R$  light curves.  $(V - R)_{\min,0}^{\phi(0.5-0.8)}$  is defined as the average color over the phase range 0.5–0.8. As our program stars have well-known reddening values, the  $(V - R)_{\min}$  colors are dereddened. The average dereddened color at minimum  $V$ -band light,  $(V - R)_{\min,0}^F$ , is  $0.28 \pm 0.02$ , where 0.02 is the dispersion about the mean. The average dereddened color over the phase range 0.5–0.8,  $(V - R)_{\min,0}^{\phi(0.5-0.8)}$ , is  $0.27 \pm 0.02$ . These values are based on a total sample of 31 stars and do not appear to depend on  $[\text{Fe}/\text{H}]$ , period,  $V$ -amplitude, or  $\Delta \log P$ . The  $[\text{Fe}/\text{H}]$  range of our program stars spans  $[\text{Fe}/\text{H}] = 0$  dex to  $[\text{Fe}/\text{H}] = -2.5$  dex, the period range spans  $P = 0.38$ – $0.78$  days, and the  $V$ -amplitude range spans  $A_V = 0.39$ – $1.35$  mag. Previous hints of  $V$ -amplitude dependence on  $(V - R)_{\min,0}^{\phi(0.5-0.8)}$  seem dispelled with the larger sample size.

Using the MACHO bulge RR0 Lyrae stars from Kunder & Chaboyer (2008), we investigate if the bulge RR0 Lyrae stars have anomalous colors as compared to the local RR Lyrae stars. The bulge RR Lyrae stars are dereddened using the Popowski et al. (2003) reddening map. The RR0 Lyrae stars in Baade's Window have approximately the same intrinsic  $(V - R)_{\min}$  as the local sample. Hence the  $(V - R)_{\min,0}$  colors of the bulge RR Lyrae stars behave in the same way as the  $(V - R)_{\min,0}$  colors of local stars. Given previous suggestions of anomalous bulge RR Lyrae colors and the wide use of RR Lyrae variables as distance indicators, such a convergence of results is particularly appreciated.

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