LOW-AMPLITUDE VARIABLES: DISTINGUISHING RR LYRAE STARS FROM ECLIPSING BINARIES

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ABSTRACT

It is not easy to identify and classify low-amplitude variables, but it is important that the classification is done correctly. We use photometry and spectroscopy to classify low-amplitude variables in a 246 deg2 part of the Akerlof et al. field. Akerlof and Collaborators found that 38% of the RR Lyrae stars in their 2000 deg2 test field were RR1 (type c). This suggests that these RR Lyrae stars belong to an Oosterhoff Type II population, while their period distribution is primarily Oosterhoff Type I. Our observations support their RR0 (type ab) classifications; however, six of the seven stars that they classified as RR1 (type c) are eclipsing binaries. Our classifications are supported by spectroscopic metallicities, line-broadening, and Galactic rotation measurements. Our 246 deg2 field contains 16 RR Lyrae stars that are brighter than mR = 14.5; only four of these are RR1 (type c). This corresponds to an Oosterhoff Type I population in agreement with the period distribution.

Key words: Galaxy: halo – Galaxy: structure – stars: horizontal-branch – stars: individual (RR Lyrae)

Online-only material: color figures, machine-readable and VO tables

1. INTRODUCTION

Low-amplitude variables are difficult to identify and classify, yet determining their true nature is astrophysically important. Lee & Carney (1999) and Miceli et al. (2008) have shown that the Oosterhoff Type I (OoI) and the Oosterhoff Type II (OoII) field RR Lyrae stars have different galactic distributions and hence, presumably, different origins. Oosterhoff Types are defined not only by the period distributions of their RR0 (type ab) and RR1 (type c) variables but also by the relative numbers of these two RR Lyrae types. Thus, the RR1 (type c) comprises 45% of all the RR Lyrae stars in the OoII globular clusters but only 20% in the OoI globular clusters (Clement et al. 2001). In recent large surveys for field RR Lyrae stars, RR1 variables comprised 17% of the total in the QUEST Survey (Vivas et al. 2004) and 22% of the total in the Sloan Digital Sky (SDSS) Stripe 82 Survey (Watkins et al. 2009) indicating OoI populations in both cases.

Akerlof et al. (2000, hereafter AAB), on the other hand, study a 2000 deg2 field of the ROTSE All-Sky Survey,3 and find that 38% of their RR Lyrae stars are RR1 (type c). Problematically, this suggests an OoII population although the period distribution shown in AAB (Figure 8) is that of a predominantly OoI population. The QUEST, SDSS, and ROTSE1 surveys all use CCD photometry which (unlike the older photographic surveys) can be used to detect the relatively low-amplitude RR1 (type c) variables with reasonable completeness. The ROTSE1 survey, for example, lists variables with amplitudes as low as 0.1 mag—significantly lower than the amplitudes of most RR1 (type c). Amrose & McKay (2001) did not include the RR1 (type c) in their discussion of the ROTSE1 RR Lyrae variables because they considered their classification less robust than that of the RR0 (type ab). We also note that the stars that AAB classify as RR1 (type c) tend to be brighter and to have lower reduced proper motions than those that they classify as RR0 (type ab); this suggests that we should review the classification of the lower amplitude RR Lyrae stars in the ROTSE1 survey.

Recently, Hoffman et al. (2009) have reclassified the brighter variables in the NSVS using Fourier coefficients. Even in this bright sample, they say “without color information and higher precision photometry, the W UMa and RRc variables cannot easily be differentiated and in their summary they cite the W UMa/RRc degeneracy problem as a major source of misclassification. Blomme et al. (2010) mention the problem in their discussion of the new Kepler data and it surely will be a problem in the pipeline analysis of Pan-STARRS and LSST variable star data.

In this paper, we consider a 246 deg2 field near the north Galactic pole (NGP) defined by 186:5 < R.A. < 204:0 and +23:0 < decl. < +39:0 (Figure 1). This is part of the 2000 deg2 test field ROTSE1. In addition to discussing the data given by AAB, we use the General Catalogue of Variable Stars (GCVS)4 and various sources discussed in Appendix A.

AAB identified 33 RR Lyrae stars in this field; one of these (J130441.22+381804.50) is the same as J130441.18+381805.1 and is ignored. AAB classified nine as RR1 (type c) and 23 as RR0 (type ab). Two of these RR1 (U Com and VW CVn) are given in the GCVS. U Com has been studied in detail (Bono et al. 2000) and its classification is secure. VW CVn, however, is classified as an eclipsing binary in both the GCVS and SIMBAD. It is also included in a recent catalog of eclipsing variables (Malkov et al. 2006). AAB classifies VW CVn as RR1 (type c) and it is clear from the light curve given by Agerer & Berthold (1994) that this classification is the correct one with a period of 0.425 days and not (as originally thought) an eclipsing system with twice this period. This confusion over the nature of a 12th magnitude star shows that the classification of RR1 variables from low signal-to-noise ratio (S/N) data is not trivial.

The 21 ROTSE1 RR Lyrae stars in our field that are in the GCVS are listed in Table 1. The ROTSE1 data for the other 11 RR Lyrae variables are given in Table 2. Further information on these stars is given in the notes to this table. Apart from VW

3 The NOAO are operated by AURA, Inc. under cooperative agreement with the National Science Foundation.

4 Hereafter called the ROTSE1 survey. We refer to the complete Northern Sky Variability Survey (Wozniak et al. 2004) as the NSVS.

5 http://www.sai.msu.su/groups/cluster/gcvs
dolt standards (Landolt 1992) were observed nightly so that Lowell Observatory using the Kron aperture photometer and 12 night run with the 42 inch John S. Hall telescope of the following black symbols: filled circles RR0 (type stars that were discovered by AAB are shown (using their classifications) by the following symbols: filled circles RR0 (type ab); open circles RR1 (type c); open triangles Delta Scuti stars. The small filled squares show the stars that AAB classified as eclipsing binaries. The survey fields of Kinman et al. (1966) are outlined by green dotted lines.

(A color version of this figure is available in the online journal.)

CVn, we assume that the GCVS classifications given in Table 1 are correct but that the classifications of the stars in Table 2 need to be checked through new photometry, spectroscopy, and a re-discussion of the NSVS photometry for these variables.

2. PHOTOMETRY OF VARIABLES

We first observed the variables in Table 2 on 9 nights of a 12 night run with the 42 inch John S. Hall telescope of the Lowell Observatory using the Kron aperture photometer and a thermoelectrically cooled EMI 6256 photomultiplier. Landolt standards (Landolt 1992) were observed nightly so that the V and (B – V) are on the Johnson system. These observations (made in 2002 May; JD 2452407–2452418) are given in Table 3. Only about ten observations were obtained for each object. Also, although the sky was apparently clear for these observations, the scatter in the V magnitudes suggests that it may not have always been perfectly photometric. The effect on the (B – V) colors was probably minor in comparison. We therefore obtained further photometric observations between 2004 and 2009 using the commercial robotic f/7 0.8 m Ritchey–Chretien telescope of the Tenagra Observatory in Arizona. The detector on this telescope was a 1024 × 1024 STIe CCD. Only the central 7” diameter field (which has excellent cosmetic quality) was used and reduced with standard IRAF routines (Tody 1993). On photometric nights the data were calibrated using local standards from an earlier program at the NGS (Kinman et al. 1994). The variable J123811.00+385028.0 and its comparison star (A) at J123806.03+385049 have also been observed by E. Schmidt (2009, private communication). He found $V = 13.848$ and $V – R = 0.372$ for the comparison star while we get $V = 13.841$ and $B – V = 0.27$ in satisfactory agreement. On non-photometric nights, the magnitudes of the variables were obtained differentially with respect to nearby stars. The positions of these comparison stars and their adopted magnitudes are given in Table 9 in Appendix C. In some cases, only relatively faint comparison stars were available in the 7” field and this limited the attainable accuracy with the relatively short exposures that were used.

The photoelectric data of 2002 are given in Table 3 and the Tenagra photometric data are given in Table 4. We also used the NSVS (Wozniak et al. 2004). Typically, these data contain many pairs of observations that are separated by about 0.0010 days and which can be combined to improve the accuracy with negligible loss of time resolution. We also rejected data if the quoted errors were relatively large.

We illustrate the problem of using photometry for classification by considering the case of one of the lowest amplitude variables (J123250.33+292123.6) (Figure 2). Our Johnson B magnitudes are not accurate enough to give an adequate light curve for a variable with such a low amplitude (Figures 2(b) and (e)). The NSVS data in $m_R$, however, give a much better light curve. We compared 12 bright RR Lyrae stars that have both $m_R$ and Johnson $B$ light curves and found that their $m_R$, $V$, and $B$ amplitudes are in the ratios of 1.00, 1.27, and 1.60, respectively. The $m_R$ amplitude of J123250.33+292123.6 is roughly 0.125 mag, so if it were a pulsating star we would expect amplitudes of 0.20 and 0.041 mag in $B$ and $(B – V)$, respectively. In Figures 2(a) and (b), we have taken the $(B – V)$ and $B$ curves of the RRc U Com (Heiser 1996), and scaled them to those of J123250.33+292123.6 using the ratio of their $m_R$ amplitudes; these curves give a poor fit to the data. For an eclipsing system, we would expect the $m_R$ and $B$ amplitudes to be equal and the color to be constant. Our $B$ photometry is not accurate enough to give a reliable amplitude for this star but the small scatter in $(B – V)$ (Figures 2(a) and (d)) and the $m_R$ light curve (Figures 2(c) and (f)) suggests that J123250.33+292123.6 is an eclipsing system with $P = 0.52428$ days rather than a pulsating star with half this period. A summary of its photometric properties is given in Section 2.2.

2.1. Comments on Stars Classified as RR Lyrae Stars

The classifications and periods derived from our photometry agree with those of AAB for the five stars with the highest amplitudes in Table 2. Their light curves are given in Figures 3 and 4. Some of the scatter in these light curves may come from using a single period for data that covers five years. Jurcsik et al. (2009) have shown that light-curve modulation is a common property of RR0 (type ab) stars and this may also contribute to the scatter (e.g., J123811.00+385028.0 where the modulation is very strong). Comments on the individual stars are given below. J123811.00+385028.0: the photoelectric data show that $(B – V)$ varies from 0.25 to 0.35 as would be expected for an RR0 star. Our photoelectric and Tenagra data (2004, 2008, and 2009), however, were inadequate to give a satisfactory light curve. In early 2009, we asked E. Schmidt to observe the star and he kindly made his observations available to us. The star clearly shows strong Blazhko effect (Figure 3) but we have been unable to determine the Blazhko period. The adopted ephemeris is $P_{\text{max}} = 2.452,407.588$ and $P = 0.533035$ days.

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6 http://www.tenagraobservatories.com

7 We use $m_R$ for the unfiltered CCD magnitudes of the NSVS survey.
Table 1

| ROTSE1 ID       | Typea   | Period (days) | $m_R$ | $A_r$ | IDd | Typee | Periodf (days) |
|-----------------|---------|---------------|-------|-------|-----|--------|----------------|
| J122907.47+343850.0 | rrab    | 0.55868       | 13.17 | 1.0   | RR CVn | RRab | 0.55860     |
| J123234.60+270145.7 | rrab    | 0.58668       | 12.20 | 1.0   | S Com  | RRab | 0.58659     |
| J123556.02+371224.9 | rrab    | 0.66847       | 12.98 | 0.7   | SV CVn | RRab | 0.66806     |
| J123757.13+295805.8 | rrab    | 0.47266       | 15.02 | 1.3   | FV Com | RRab | 0.47246     |
| J124004.01+273104.0 | rrc     | 0.29278       | 11.57 | 0.3   | U Com  | RRe  | 0.29273     |
| J124255.05+370507.0 | rrab    | 0.44169       | 13.20 | 0.8   | SW CVn | RRab | 0.44165     |
| J124354.34+280114.0 | rrab    | 0.54080       | 15.11 | 1.0   | DV Com | RRab | 0.54084     |
| J124716.30+351206.0 | rrab    | 0.61849       | 15.10 | 1.2   | DS CVn | RRab | 0.61843     |
| J125000.65+310824.4 | rrab    | 0.53654       | 14.75 | 1.0   | TX Com | RRab | 0.53647     |
| J125110.42+325808.3 | rrab    | 0.57463       | 13.38 | 0.4   | AP CVn | RRab | 0.57465     |
| J125421.57+321433.3 | rrab    | 0.51345       | 14.11 | 0.9   | TY CVn | RRab | 0.51344     |
| J125455.50+231526.3 | rrc     | 0.29278       | 11.57 | 0.3   | U Com  | RRc  | 0.29273     |
| J125952.34+301432.6 | rrab    | 0.53235       | 14.75 | 0.9   | UW Com | RRab | 0.53233     |
| J130129.21+320512.3 | rrab    | 0.55198       | 14.63 | 1.1   | TZ CVn | RRab | 0.55187     |
| J130213.65+241419.6 | rrc     | 0.66163       | 13.95 | 0.8   | BF Com | RRab | 0.66141     |
| J130507.95+231642.8 | rrab    | 0.46901       | 13.09 | 0.9   | RY Com | RRab | 0.46895     |
| J131226.95+302117.9 | rrab    | 0.73723       | 13.64 | 0.5   | UZ Com | RRab | 0.73694     |
| J131703.38+302117.9 | rrab    | 0.67783       | 15.10 | 1.0   | DZ CVn | RRab | 0.67732     |

Notes.

- a Type given by Akerlof et al. (2000) rrab = RR0; rrc = RR1.
- b Unfiltered CCD mean magnitude of variable.
- c Unfiltered CCD amplitude of variable.
- d Identification in GCVS.
- e Variable type given in GCVS.
- f Period given in GCVS.

Table 2

| ROTSE1 ID       | Typea   | Period (days) | JD Maxb | $D^c$ | $m_R$ | $A_r$ | Qb     | Note |
|-----------------|---------|---------------|---------|--------|-------|-------|--------|------|
| J123250.33+292123.6 | rrc     | 0.26217 ± 0.00003 | 51244.6032 | 0.5 | 11.68 | 0.1 | 6 | (1) |
| J123811.00+385028.0 | rrab    | 0.53331 ± 0.00006 | 51246.6095 | 0.2 | 13.94 | 1.1 | 5 | (2) |
| J123854.21+25307.9 | rrab    | 0.62841 ± 0.00014 | 51244.9048 | 0.4 | 13.24 | 0.3 | 9 | (3) |
| J124855.82+331934.5 | rrc     | 0.20415 ± 0.00002 | 51244.8268 | 0.5 | 12.51 | 0.2 | 5 | (4) |
| J125947.50+365843.6 | rrab    | 0.30817 ± 0.00002 | 51244.5879 | 0.2 | 10.62 | 0.3 | 5 | (5) |
| J13041.18+381805.1 | rrab    | 0.68636 ± 0.00011 | 51246.8109 | 0.3 | 14.03 | 0.9 | 6 | (6) |
| J13070.50+365757.1 | rrab    | 0.22348 ± 0.00002 | 51244.5912 | 0.4 | 11.59 | 0.2 | 5 | (7) |
| J13284.66+36057.1 | rrc     | 0.58633 ± 0.00016 | 51246.6046 | 0.5 | 14.87 | 0.8 | 6 | (7) |
| J13304.36+35535.8 | rrab    | 0.35292 ± 0.00005 | 51246.6543 | 0.5 | 14.30 | 0.7 | 5 | (7) |
| J13326.15+35533.7 | rrc     | 0.28913 ± 0.00007 | 51246.8027 | 0.9 | 11.16 | 0.1 | 5 | (8) |
| J13334.47+351949.5 | rrc     | 0.35983 ± 0.00006 | 51246.4898 | 0.5 | 13.14 | 0.3 | 6 | (9) |

Notes.

- a Type given by Akerlof et al. (2000) rrab = RR0; rrc = RR1.
- b Period in days (and error).
- c Julian Date of maximum light (+2,400,000).
- d Accumulated phase error after 3 years.
- e Unfiltered CCD mean magnitude of variable.
- f Unfiltered CCD amplitude of variable.
- g Quality on scale 10 (excellent) downward.

J123854.21+245307.9: Type RR0 (type ab). The adopted ephemeris is JD(max) = 2,451,244.905 and $P = 0.62839$ days with a $V$ amplitude of 0.33 mag and $(B - V)$ amplitude of 0.12.

J13044.18+381805.1: Type RR0 (type ab). The adopted ephemeris is JD(max) = 2,451,246.880 and $P = 0.686270$ days with a $V$ amplitude of 0.85 mag and $(B - V)$ amplitude of 0.18.
Figure 2. Light curves for J123250.33+292123.6. Open circles show the Lowell photoelectric data (2002). Filled circles show the Tenagra CCD photometry (2008, 2009). The open triangles show the light curves derived from NSVS photometry (1999, 2000). The plots on the left are for a period of 0.262140 days and those on the right are for a period of 0.524280 days which is the preferred interpretation. The curves in panels (a) and (b) are those that would be expected if the star were an RRc variable; it is seen that they do not fit the data.

Table 3

| ROTSE1 ID         | JDH | V  | (B−V) | Phase |
|-------------------|-----|----|-------|-------|
| J123250.33+292123.6 | 52407.8184 | 11.422 | 0.378 | 0.691 |
| J123250.33+292123.6 | 52408.8117 | 11.371 | 0.374 | 0.585 |
| J123250.33+292123.6 | 52409.6892 | 11.450 | 0.376 | 0.259 |
| J123250.33+292123.6 | 52411.6874 | 11.414 | 0.380 | 0.071 |
| J123250.33+292123.6 | 52411.7903 | 11.440 | 0.377 | 0.267 |
| J123250.33+292123.6 | 52416.7395 | 11.457 | 0.375 | 0.707 |
| J123250.33+292123.6 | 52417.7894 | 11.419 | 0.367 | 0.709 |
| J123250.33+292123.6 | 52418.7218 | 11.440 | 0.373 | 0.488 |

Notes.

- Heliocentric Julian Date (+2,400,000).
- Johnson V magnitude.
- Johnson (B−V) color.
- Phase for ephemeris given in text.

(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.)

Table 4

| ROTSE1 ID         | JDH | V  | B  | Phase |
|-------------------|-----|----|----|-------|
| J123250.33+292123.6 | 54543.8937 | ... | 11.77 | 0.993 |
| J123250.33+292123.6 | 54574.7290 | ... | 11.82 | 0.808 |
| J123250.33+292123.6 | 54575.6632 | ... | 11.85 | 0.590 |
| J123250.33+292123.6 | 54578.7472 | ... | 11.66 | 0.472 |
| J123250.33+292123.6 | 54579.6928 | ... | 11.77 | 0.276 |
| J123250.33+292123.6 | 54580.7074 | ... | 11.85 | 0.211 |
| J123250.33+292123.6 | 54845.0301 | ... | 11.75 | 0.374 |
| J123250.33+292123.6 | 54846.0272 | ... | 11.83 | 0.276 |
| J123250.33+292123.6 | 54847.0444 | ... | 11.83 | 0.216 |
| J123250.33+292123.6 | 54847.0548 | ... | 11.85 | 0.236 |

Notes.

- Heliocentric Julian Date (+2,400,000).
- Johnson V magnitude.
- Johnson B magnitude.
- Phase for ephemeris given in text.

(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.)

2.2. Comments on Stars Classified as Eclipsing Binaries

The remaining six stars in Table 2 have $m_R$ amplitudes of $\lesssim 0.3$ mag and were classified by AAB as RR1 (type c) variables. They do, however, have a very low amplitude or constant $(B−V)$ and so it is unlikely that they are pulsating stars. Support for this comes from their $m_R$ light curves which use NSVS magnitudes. We used a periodogram program (Horne & Baliunas 1986)

J132849.66+360757.1: Type RR0 (type ab). The adopted ephemeris is JD(max) = 2452,407.365 and $P = 0.586186$ days with a $V$ amplitude of 0.73 mag and $(B−V)$ amplitude of 0.10.

J133048.36+335353.8: this is the only confirmed RR1 (type c). The adopted ephemeris is JD(max) = 2451,274.511 and $P = 0.353000$ days with a $V$ amplitude of 0.42 mag and $(B−V)$ amplitude of 0.15.

In all cases the light curves are significantly asymmetric and there is a significant color amplitude so that the RR classification seems secure.
to find the periods; these were close to those given by AAB. We then doubled these periods before deriving the light curves (Figure 5). In all cases, this double period gave two minima of slightly unequal depth at phases 0.25 and 0.75 and the maxima were sometimes somewhat flattened. Figure 6 shows the Lowell \(B - V\) observations for these stars together with the color curves that would be expected if these stars were RR\(c\). As in Figure 2, these curves were obtained by scaling the colors of U Com. The colors of these variables are generally significantly redder than that of U Com and do not show the phase variation of this RR\(c\).

Details for the individual variables are given below.

J123250.33+292123.6: (A) the adopted ephemeris is JD(max) = 2,451,244.603 and \(P = 0.524280\) days. The \(m_R\) amplitudes are roughly 0.110 and 0.125 mag. \((B - V)) = 0.375\) mag and the rms scatter in \((B - V)) of a single observation = 0.005 mag.

J124855.82+331934.5: (E) the adopted ephemeris is JD(max) = 2,451,244.827 and \(P = 0.408280\) days. The \(m_R\) amplitudes are roughly 0.11 and 0.16 mag. \((B - V)) = 0.286\) mag and the rms scatter in \((B - V)) of a single observation = 0.012 mag.

J125947.50+365843.6: (G) the adopted ephemeris is JD(max) = 2,451,244.609 and \(P = 0.616285\) days. The \(m_R\) amplitudes are roughly 0.20 and 0.26 mag. \((B - V)) = 0.222\) mag.

and the rms scatter in \((B - V)) of a single observation = 0.009 mag.

J130705.50+365757.1: (I) JD(max) = 2,451,244.614 and \(P = 0.44721\) days. The \(m_R\) amplitudes are roughly 0.11 and 0.13 mag. \((B - V)) = 0.608\) mag and the rms scatter in \((B - V)) of a single observation = 0.003 mag. The \((B - V)) color is too red for this to be an RR Lyrae star.

J133204.15+385533.7: (M) JD(max) = 2,451,244.790 and \(P = 0.578340\) days. The \(m_R\) amplitudes are roughly 0.05 and 0.07 mag. \((B - V)) = 0.239\) mag and the rms scatter in \((B - V)) of a single observation = 0.005 mag.

J133234.47+351949.5: (N) JD(max) = 2,451,244.454 and \(P = 0.720306\) days. The \(m_R\) amplitudes are roughly 0.18 and 0.22 mag. \((B - V)) = 0.424\) mag and the rms scatter in \((B - V)) of a single observation = 0.018 mag.

All the above stars are reclassified as eclipsing binaries.

3. SPECTROSCOPY

Spectra can be used to distinguish high-metallicity foreground eclipsing stars of the disk from low-metallicity variables that belong to the extended low-rotation halo. We obtained short integrations with the MMT blue-channel spectrograph of all the stars in Table 2 except J130705.50+365757.1. Details of these flux-calibrated spectra (that cover \(\lambda\lambda 3600–4500\) Å) are given in Table 5. The spectral resolution was 1.0 Å for all the spectra except those of J133204.15+385533.7 and J133234.47+351949.5 for which it was 1.2 Å. The spectra have S/N in the range 50–100 and yield radial velocities with accuracies of \(2–3\) km s\(^{-1}\); the Balmer lines and Ca\(\text{ii}\) K-line equivalent widths can be used to determine the metallicity ([Fe/H]).

No calibrating standard stars were observed, however, so we could only measure pseudo-equivalent widths from which non-standard metallicities were derived. We denote these by \([m/\text{H}]^*\).

3.1. Metallicities and Rotations

Preston (1959) showed that the difference between the spectral types of the Balmer lines and the Ca\(\text{ii}\) K-line of RR Lyrae stars at minimum light gives an index (\(\Delta S\)) that measures the metallicity of the star. These spectral types should be derived from the equivalent widths using a calibration given by spectra of stars of known spectral type that are taken concurrently with those of the program stars. Since we had no standards, we used the equivalent width versus spectral-type calibration given by Kinman & Carretta (1992); the resulting non-standard indices (denoted by \(\Delta S^*\)) were converted to \([m/\text{H}]^*\) using the calibration of Suntzeff et al. (1994). These metallicities are approximate not only because of the rough calibration of the equivalent widths but also because some of the spectra were taken at phases near maximum light where the conversion of \(\Delta S\) to [Fe/H] is known to be inaccurate. Despite these limitations, the mean \(\Delta S^*\) for the RR Lyraes (+4.6 ± 1.0) differs significantly from that of the eclipsing stars (−1.9 ± 1.8) in the sense that the RR Lyrae stars have halo abundances ([Fe/H] < −0.8) while those of the eclipsing stars are more nearly solar (Table 5).

The metallicities of RR Lyrae stars can also be derived from their light curves. Smooth curves (drawn by eye through the data points) were used to derive the Fourier coefficient \(\phi_1\), the \(V\) amplitude, and the rise time. Non-standard metallicities \([m/\text{H}]^*\) were then derived from these quantities using Equations (3), (6), and (7), respectively, of Sandage (2004). The use of hand-drawn light curves necessarily gives approximate results but we
Figure 4. Light curves for J123854.21+245307.9, J130441.18+381805.1, J132849.66+360757.1, and J133048.36+335353.8. They are based on both the Lowell photoelectric and Tenagra CCD data and cover the years 2002, 2004, 2008, and 2009. $V$ magnitudes are shown as filled circles and $B$ magnitudes as open circles. All these stars are classified as RR Lyrae stars.

Figure 5. Light curves for J123250.33+292123.6, J124855.82+331934.5, J125947.50+365843.6, J130705.50+365757.1, J133204.15+385533.7, and J133234.47+351949.5. The $m_R$ magnitudes were taken from the NSVS. All these stars are reclassified as eclipsing binaries.
see (Table 6) that these three metallicity estimates not only agree well among themselves but also with the spectroscopic values. Our adopted [m/H]⁎ is based on the three photometric and the spectroscopic values. Also, the [m/H]⁎ of −0.9 and −1.9 that we adopt for J123854.21+245307.9 and J130441.18+381805.1 are in reasonable agreement with the −1.2 and −2.2 respectively that Kinemuchi et al. (2006) give for these stars.

We also measured the width (FWHM of a Gaussian fit) of the Mg ii λ4481 doublet (Table 5). This width is frequently used as a measure of rotational broadening (Slettebak 1954). In our
data, this width is significantly larger for the eclipsing systems than for the RR Lyrae stars. The RR Lyrae stars are known to have quite narrow lines (Peterson et al. 1996), while those of the eclipsing systems should be broadened both by rotation and orbital motion. This broadening should be least for those that are seen pole-on and thus for those with the lowest amplitudes. It is seen in Figure 7, that, in the case of the eclipsing stars, the FWHM of the Mg II λ4481 line does indeed decrease with the decreasing amplitude of the star. Extrapolated to zero amplitude, this width would be about 2.4 Å. This may be compared with the mean width for the RR Lyrae stars (1.7 ± 0.15 Å) which presumably is close to the instrumental width.

3.2. Absolute Magnitudes, Distances, and Galactic Rotation

Absolute magnitudes for the RR Lyrae stars were obtained from

$$M_v = 0.214[\text{Fe/H}] + 0.86$$

(1)

using the coefficients given by Clementini et al. (2003). Absolute magnitudes for the eclipsing systems were obtained from the calibration for W UMa-type binary stars given by Rucinski (2000):

$$M_v = -4.44 \log P + 3.02(\gamma - V)_0 + 0.12.$$  

(2)

The distances given in Table 6 are based on these $M_v$. Then, following Johnson & Soderblom (1987), the radial velocities (Table 5) and proper motions (UCAC3 catalog: Zacharias et al. 2010) were used to calculate the heliocentric galactic rotation velocities ($V$) given in Table 6. The radial velocities that we give for the RR Lyraes is quite different from that which we find for the eclipsing stars; they correspond to what we would expect for halo and disk stars, respectively.

The galactic rotations in Table 6 are only valid if our reclassifications are correct. We have therefore repeated the calculations assuming that the six stars that we have reclassified as eclipsing binaries are in fact RRc stars as originally classified by AAB. The results are shown in Table 7. In this case, the mean galactic rotation of the six stars that we reclassified is $-45 \pm 31$ km s$^{-1}$ and the dispersion in $V$ for these stars is $69 \pm 20$ km s$^{-1}$. Thus, the galactic rotation ($V$) alone only tells us that these six stars could be disk stars and either be eclipsing binaries or metal-rich disk RR Lyrae stars. The most doubtful

### Table 6

| ROTSE1 ID     | Type$^a$ | $\phi_3$ | [m/H]$^{b,c}$ | [m/H]$^{d,e}$ | [m/H]$^{f}$ | [m/H]$^{g}$ | $M_v^h$ | Distance$^i$ | $V^j$ |
|---------------|---------|----------|---------------|--------------|-------------|------------|---------|-------------|-----|
| RR Lyrae stars: |         |          |               |              |             |            |         |              |     |
| J12381.90+385028.0 | RR0 | 2.39 | −0.96 | −0.74 | −0.84 | −0.66 | −0.8 | +0.69 | 3.70 | −180 ± 055 |
| J123854.21+245307.9 | RR0 | 2.67 | −0.77 | −0.85 | −1.01 | −0.80 | −0.8 | +0.68 | 2.89 | −189 ± 047 |
| J130441.18+381805.1 | RR0 | 1.94 | −1.6 | −2.14 | −2.07 | −1.59 | −1.9 | +0.44 | 4.17 | −340 ± 067 |
| J132849.66+360757.1 | RR0 | 2.54 | −1.0 | −0.82 | −1.35 | −0.90 | −1.0 | +0.65 | 6.02 | −435 ± 300 |
| J133048.36+335353.8 | RR1 | 2.43 | −1.36 | −1.8 | ... | ... | −1.4 | +0.57 | 2.75 | −115 ± 044 |
| Eclipsing systems: |      |          |               |              |             |            |         |              |     |
| J123250.33+291223.6 | EW | ... | ... | ... | ... | ... | +2.43 | 0.62 | +025 ± 04 |
| J124855.82+331934.5 | EW | ... | ... | ... | ... | ... | +2.68 | 0.79 | −004 ± 16 |
| J125947.50+365843.6 | EW | ... | ... | ... | ... | ... | +1.68 | 0.49 | −064 ± 03 |
| J130705.50+365757.1 | EW | ... | ... | ... | ... | ... | +3.46 | 0.37 | (−022 ± 26) |
| J133204.15+385533.7 | EW | ... | ... | ... | ... | ... | +1.88 | 0.58 | −007 ± 04 |
| J133234.47+351949.5 | EW | ... | ... | ... | ... | ... | +1.99 | 1.43 | −072 ± 16 |

Notes.

$^a$ Type derived by our photometry: RRab = RR0; RRc = RR1.

$^b$ Fourier coefficient derived from hand-drawn light curve.

$^c$ Non-standard [m/H] derived from the spectra.

$^d$ Non-standard [m/H] derived from the Fourier coefficient $\phi_3$.

$^e$ Non-standard [m/H] derived from the V amplitude.

$^f$ Non-standard [m/H] derived from the Rise-time (phase difference between minimum and following maximum).

$^g$ Adopted non-standard [m/H]$^*$.  

$^h$ Absolute magnitude derived as described in the text.

$^i$ Distance in kpc.

$^j$ Galactic velocity vector ($V$) in km s$^{-1}$.
classification is that of J133234.47+351949.5 whose galactic rotation $V$ and metallicity are compatible with it belonging to the halo. The large FWHM of its Mg $\lambda4481$ line, however, makes it more likely that it is an eclipsing binary.

As would be expected for a disk population, the six stars that we reclassified as eclipsing systems have essentially zero mean radial velocity ($-22 \pm 20$ km s$^{-1}$). The RR Lyrae stars, on the other hand, show a mean radial velocity that is strongly negative ($-135 \pm 45$ km s$^{-1}$). This downward streaming of halo stars at the NGP was first discovered among subdwarfs by Majewski et al. (1994, 1996). Similar streaming in this part of the sky has since been also found among RR Lyrae and BHB stars (Kinman et al. 1996). Similar streaming in this part of the sky has since been also found among RR Lyrae and BHB stars (Kinman et al. 1996). The velocities in Table 5 give further confirmation of the effect. This downward motion toward the plane occurs a few kpc above the plane but does not continue to the solar neighborhood (Seabroke et al. 2008); it presumably is one of the many tidal streams that are known to exist in the halo.

4. SUMMARY

We use Johnson $BV$ photometry and MMT spectroscopy to study 11 stars (Table 2) classified by AAB as RR Lyraes. Our observations support the RR Lyrae classifications for the five stars with the largest amplitudes, however, we find that the six low-amplitude stars classified by Akerlof et al. (2000) as RR1 (type $c$) should be reclassified as eclipsing binaries. We derive metallicities from both spectra and light curves and find a halo abundance for the RR Lyrae stars and a solar abundance for the eclipsing binaries.

The FWHM line widths of the Mg $\Pi \lambda4481$ line provide a clean separation between RR Lyrae stars and eclipsing variables so that, in principle, a single moderate S/N spectrum with a resolution of 1 Å can provide enough information to distinguish between a pulsating variable and an eclipsing binary even when the amplitude is quite low. Supporting evidence comes from the absence of color variation in eclipsing variables and the differing kinematics of the two types of variables.

Our observations resolve the problematic over-abundance of RR1 (type $c$) reported by AAB. They found that 38% of their RR Lyrae stars were RR1 (type $c$), yet about half of this number would have been expected from the Oo I period distribution of these stars. In our 246 deg$^2$ field, there are 16 RR Lyrae stars with $m_R \leqslant 14.5$. We find four RR1 (type $c$), including BS Com discussed in Appendix A, and 12 RR0 (type $ab$). Thus in our small sample, 25% of the RR Lyrae stars are RR1 (type $c$); this is in statistical agreement with that expected from the period distribution. In the future, it would be desirable to investigate the classification of larger samples of the lower-amplitude RR Lyrae stars from the AAB test fields. Also many of the RR1 (type $c$) variables in the ASAS catalog are also classified as possible eclipsing stars; reclassification of these stars using the techniques suggested here would also be very desirable.

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APPENDIX A

THE SURVEY FIELD AND PREVIOUS SURVEYS IN THIS LOCATION

Figure 1 shows the location of our survey field. The declination limits of +23°0 and +39°0 and the R.A. limit of 186°5
were set by the limits of the test field of AAB (Akerlof et al. 2000). The other R.A. limit (204°:0) was chosen so that the field is roughly symmetrical about the NGP (R.A. 192°:859, decl. +27°:128). The RR Lyrae stars listed in the GCVS are shown as large open red pentagons. The remaining symbols (in black) show the stars that are listed by AAB according to the following AAB classifications: filled circles RR0 (type ab); open circles RR1 (type c); and open triangles Delta Scuti stars. The small filled squares are the stars that AAB classified as eclipsing binaries.

Figure 8 shows the distribution of RR0 (type a) stars and RR1 (type c) stars as a function of their 2MASS $J$ magnitude. These distributions are shown separately for the ROTSE1 and the GCVS classifications. The stars classified as RR1 (type c) are generally brighter than RR0 (type ab) in the ROTSE1 survey. This is not true for the GCVS classifications. In the top panel (a) of Figure 8, we have marked with crosses the three stars that we classify as RR1 (type c); we classify the remainder as eclipsing systems.

The 81 deg$^2$ of our field south of decl. +28°:0 is also covered by the ASAS-3 catalog (Pojmanski 2002). Among the variables with periods of less than a day in the two surveys, there are six stars in ASAS-3 that are not given by AAB; they are listed in Table 8. Two of these have amplitudes and colors that make them possible RR Lyrae stars. 133439+2416.6 (BS Com) has recently been shown to be a double-mode RR Lyrae star with fundamental and overtone periods of 0.487 and 0.363 days and amplitudes of 0.12 and 0.23 mag, respectively (Bragaglia et al. 2003; Wils 2006; Szczygiel & Fabrycky 2007). Dĕkány (2007) has made detailed observations of BS Com; Figure 4 in his paper shows how the amplitude of this variable varies through its cycle; an extensive set of data is needed to recognize such variables and this, perhaps, is why it was missed by AAB.

Surveys for fainter RR Lyrae stars (roughly 12 < $V$ < 17) include the Sonneberg surveys which cover the same R.A. range as our field for decl. south of +25°:0 (Meinunger 1977) and the Survey with the Lick Carnegie Astrograph (Kinman et al. 1966) in the region shown by the dotted green lines in Figure 1. Smaller deep surveys have been made by Pinto & Romano (1973), Erastova (1979) and the CCD transit survey at +28°:0 and width 8:2 by Wetterer et al. (1996). Most of the stars discovered in these surveys are included in the GCVS and cover roughly half of the total area of our field. The Lick Survey is known to be incomplete for variables with $B$ amplitudes less than 0.75 mag, and this is presumably true of these other photographic surveys. In addition to the ASAS-3 survey, other new surveys for the brighter variables include the SAVe CCD survey (Maciejewski & Niedzielski 2005) that covers the part of our region with R.A. > 190°:0 and south of +29°:0 and lists five red variables (9.0 < $V$ < 10.0) that are not listed in AAB. The SuperWASP survey (Pollacco et al. 2006; Norton et al. 2007) started in 2004 and includes 7:8 × 7:8 fields centered on decl. +28°:0 at all R.A. It uses unfiltred CCDs and includes stars in the magnitude range 8–15; a catalog of the variables in this field is being compiled (A. Norton 2009, private communication) and should provide a valuable supplement to the NSVS catalog.

The NSVS has also been searched for RR Lyrae variables by Wils et al. (2006) and Kinemuchi et al. (2006). In addition to the variables found by AAB, Wils et al. rediscovered the RR0 variables WX CVn (NSVS 7695165) and CY Com (NSVS 7621236).
Table 9

| Variable ID | Comp. Star | R.A. (2000)a (deg) | Decl. (2000)b (deg) | Vc | Bd | (J − K) |
|-------------|------------|-------------------|-------------------|----|----|---------|
| J123250.33+292123.6 | A | 188.1950 | +29.3739 | ... | 14.11 | 0.346 |
| J123811.00+385028.0 | B | 189.5493 | +38.8263 | 16.53 | ... | 0.662 |
| J123854.21+245307.9 | A | 192.1793 | +24.3364 | ... | 15.97 | 0.871 |
| J124855.82+331934.5 | C | 195.0234 | +33.3493 | ... | 15.72 | 0.664 |
| J125947.50+365843.6 | B | 196.2226 | +36.3304 | 15.49 | ... | 0.568 |
| J130441.18+381805.1 | B | 196.8192 | +38.9774 | ... | 14.13 | 0.587 |
| J130705.50+365757.1 | B | 197.5330 | +36.9761 | ... | 15.44 | 0.234 |
| J132849.66+360757.1 | B | 202.2527 | +36.3087 | 12.84 | ... | 0.663 |
| J133048.38+335353.8 | A | 202.0177 | +33.1046 | 14.93 | 15.70 | 0.539 |
| J133204.15+385533.7 | C | 202.2241 | +36.0924 | 14.97 | 15.56 | 0.395 |
| J133234.47+351949.5 | D | 203.0287 | +35.3895 | 15.02 | 15.73 | 0.351 |

Notes.

a R.A. in decimal degrees.
b Decl. in decimal degrees.
c V magnitude.
d B magnitude.

Figure 10. ((J − K)0 vs. logarithm of period (days) for (a) stars in the local neighborhood and (b) for stars in the field of Figure 1. Eclipsing systems are shown either by small filled or large open (black) circles. RR Lyrae stars shown by large filled red circles. Stars that we reclassified as eclipsing binaries are shown in (b) as red crosses. Delta Scuti stars are shown by triangles. Horizontal lines show the effect of doubling the period. The dashed curve is the approximate boundary between the eclipsing boundary and the RR Lyrae stars.

(A color version of this figure is available in the online journal.)

There are no globular clusters in this field but M 3 is several tidal radii outside the field at R.A. = 205:546 and decl. = +28:376. The RR0 variables in this cluster have 15.49 < V < 15.79 and the RR1 variables 15.27 < V < 15.71 (Cacciari et al. 2005). These are too faint to be of concern in this paper.

APPENDIX B

ON THE CONFUSION OF RR1 (TYPE c) VARIABLES WITH CONTACT BINARIES IN THE COLOR–PERIOD PLOT

Contact binaries form a sequence in a color–period plot (Eggen 1961); Figure 10 shows this plot in the region where confusion between these variables and RR Lyrae and δ-Scuti stars is most likely. Figure 10(a) gives the plot of (J − K)0 versus log P in which nearby contact binaries (Rucinski 2006; Rucinski & Pribulla 2008) are shown as black filled circles and early-type eclipsing systems (Eggen 1961; Eggen 1978) are shown as black open circles. In this paper, magnitudes are corrected for galactic extinction following Schlegel et al. (1998). The black dashed curve shows the lower bound in this plot for the eclipsing systems. Known nearby RR1 (type c) variables are shown in Figure 10(a) by red filled circles and there is a small overlap between these variables and the eclipsing systems on this plot. Figure 10(b) shows the same plot for the ROTSE1 data. Here two Delta Scuti stars are shown by red filled triangles. The red open triangle is a star (Vmax = 11.80, V amplitude 0.37 mag) at 13h12m29s; +25°14'30" that is classified as a Delta Scuti variable (period 0.1854 days) in the ASAS-3 Survey (Pojmanski 2002) and as an eclipsing variable (P = 0.37089 days) in the ROTSE1 Survey. The three stars that we have classified as RR1 (type c) are shown by large filled red circles. The six stars that AAB classified as RR1 would be located by the small filled...
circles if this classification were correct and by the large crosses if they are (as we believe) eclipsing systems. It is seen that their reclassification as eclipsing systems relocates them in the color–period plot to a place that should be well populated by eclipsing stars.

APPENDIX C
THE COMPARISON STARS

Table 9 gives the positions and adopted magnitudes for the comparison stars for the variables that are discussed in Section 2. The positions are from the UCAC3 catalog (Zacharias et al. 2010) except for that of the comparison star of J133234.47+351949.5 which is from the NOMAD catalog (Zacharias et al. 2004). The $(J − K)$ color is taken from the 2MASS catalog.

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