CSIRO PUBLISHING

Publications of the Astronomical Society of Australia, 2012, **29**, 72–77
http://dx.doi.org/10.1071/AS11046

RR Lyrae Stars in the Globular Cluster NGC 6101

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Abstract: *V*- and *I*-band observations were taken over 9 months to study the RR Lyrae population in the metal-poor diffuse globular cluster NGC 6101. We identify one new variable, which is either a potential long-period red giant variable or eclipsing binary, and recover all previously identified RR Lyraes. One previously studied RR Lyrae is reclassified as an RRc type, while two period estimations have been significantly refined. We confirm that NGC 6101 is Oosterhoff type II with a high ratio of $n(c)/n(ab+c) = 0.833$ with a very long mean RRab period of 0.86 d. By using theoretical RR Lyrae period-luminosity-metallicity relations, we use our *V*- and *I*-band RR Lyrae data to gain an independent estimate of the reddening towards this cluster of $E(B-V) = 0.15 \pm 0.04$ and derive a distance of 12.8 ± 0.8 kpc. The majority of the work in this study was undertaken by upper secondary school students involved in the Space to Grow astronomy education project in Australia.

Keywords: globular clusters: individual (NGC 6101) — RR Lyrae variable

Received 2011 September 12, accepted 2011 December 14, published online 2012 February 24

1 Introduction

RR Lyraes variable stars are important tools in determining the distances to globular clusters in our galaxy, as well as providing useful bounds on metallicity estimates. However, our knowledge of the RR Lyrae populations of quite a number of globular clusters is lacking (Clement 2001; Catelan et al. 2006). To add to this store of knowledge, the RR Lyraes within globular cluster NGC 6101 were chosen as our object of study in mid-2010. NGC 6101 is a metal-poor ([Fe/H] $= -1.98$; Harris 1996 (2010 Edition)) southern low central concentration globular cluster located at $\alpha = 16$ h 25 m 48 s $\delta = -72°12'07''$. Prior to this latest metallicity estimate, values for [Fe/H] ≈ 1.8 were more typical (Sarajedini et al. 1991, Geisler et al. 1995, Harris 1996, Rutledge et al. 1997, Rosenberg et al. 2000, Sarajedini et al. 2007, Dotter et al. 2010), while there is also a study that suggests that [Fe/H] may be ≈ 2.1 (Kraft & Ivans 2003). This cluster had previously only been studied via photographic plates (Alcaino 1974; Liller 1981), where 10 RR Lyraes were identified, but their periods were not determined, and their mean magnitudes could only be roughly estimated.

During the course of our observations, however, another CCD study of the RR Lyrae population in NGC 6101 was published by Cohen (Cohen et al. 2011). In this paper we build on Cohen's study by adding a newly identified potential small-amplitude red variable (SARV) or eclipsing binary as well as updating the periods and reclassifying two RR Lyrae variables. We also provide a longer timebase (≈ 9 months, vs. 5 days) and more staggered light-curve data as well as providing additional *I*-band observations to provide an independent estimate of the reddening and extinction towards this cluster together with a new estimate of the distance. As our study follows fairly closely after the Cohen et al. (2011) study and there have been no intervening publications on this cluster, we wish to avoid needless repetition. Consequently, we refer the reader to Cohen et al. (2011) for a more detailed literature review on this cluster. The majority of the work within this study was undertaken by Year 11 high school students in Sydney, New South Wales, Australia as part of a large-scale astronomy education initiative, Space to Grow, which is also briefly described.

2 Observations

V- and *I*-band observations of cluster NGC 6101 were taken over 31 nights between June 2010 and April 2011 using the Merope CCD camera attached to the robotically controlled 2-metre Faulkes Telescope South at Siding Spring Observatory, NSW, Australia. The pixel scale of the camera was $0.2785''$/pixel in 2×2 binning mode with a 4.7×4.7 arcminute square field of view. As the cluster

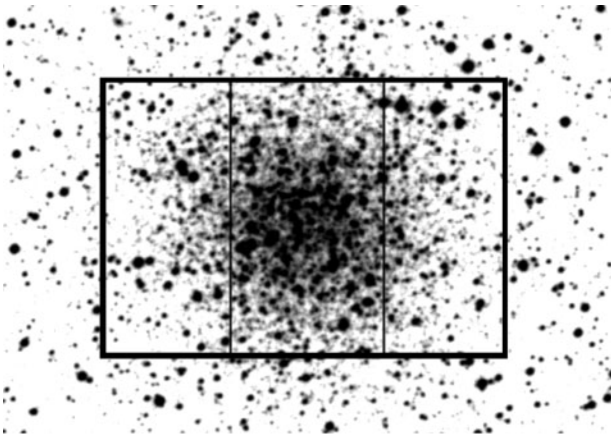

Figure 1 Image of NGC 6101 area from DSS (Red) with overlay showing typical observation field of view (6.75 × 4.7 arcminutes). NE is at top left.

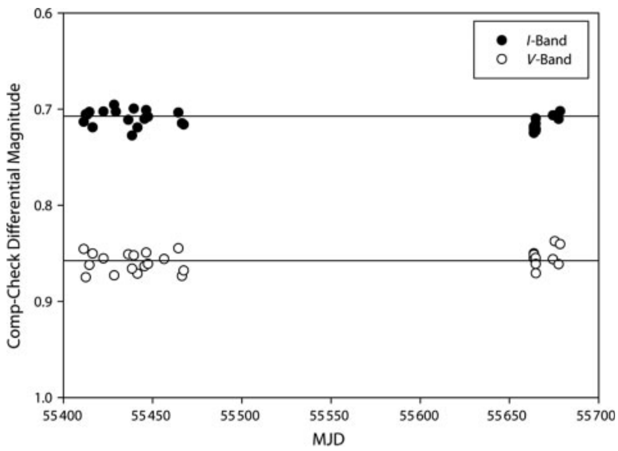

Figure 2 Comparison versus check-star magnitudes showing stability (RMS ≈ 0.01 mags) between observations.

itself is larger than this field of view, twso images per observation per filter were taken with a significant central overlap to also help eliminate a column defect in the camera (see Figure 1). The typical seeing in these images was ≈1.5 arcseconds. Bias and flat-field frames were taken and the science frames reduced at the telescope automatically prior to delivery to the observer. Observations of Landolt standard stars Mark A 1, 2, 3 and SR109-71 (Landolt 1992) were used to calibrate the images to the standard Johnson–Cousins system, for which a photometric solution with an RMS of 0.01 mag was achieved.

3 Discussion

3.1 Aperture Photometry

Observations of NGC 6101 were taken in the *V* and *I* bands by the Faulkes Telescope South over two main seasons: one over August and September 2010 and a further season to help refine the periods in April 2011. Aperture photometry using a 2.8 arcsecond–radius aperture was performed through Makali'i software for all measured stars, with the sky estimated from representative patches of dark sky from the largely star-free edges of the images. While point spread function (PSF) photometry would have been preferred, we were limited to our choice of methodology due to reasons outlined in Section 4. However, due to the quite diffuse nature of this globular cluster, aperture photometry performed well. The stability of the comparison star over all observations was found by comparison to a check star, which was found to be ≈0.01 mags RMS in both bands (shown in Figure 2). The comparison star used was found to have an apparent magnitude of $V = 14.65 \pm 0.01$ and $I = 13.34 \pm 0.01$ from the photometric solution. *V*- and *I*-band magnitudes measured for each RR Lyrae are provided as online supplementary material.

Other variables in the field of view were found by using the Find Variables function within Muniwin, a simple Windows-based automated aperture photometry variable star package. The 10 original RR Lyraes from Liller (1981) and one RR Lyrae later discovered by Cohen et al. (2011) were independently recovered using this method as well as one new variable. The new variable is probably a small-amplitude long-period variable or eclipsing binary (V23: RA 16:26:01.62, Dec –72:12:29.78) (see Section 3.4). We have continued using the naming convention set by Liller (1981) and continued by Cohen et al. (2011). A finder chart for those stars available in our field of view is given in Figure 3. Differential aperture photometry with respect to the comparison star was used to determine the apparent magnitudes for each variable star in both *I* and *V*. An ANOVA period-finding method within the Peranso software was used to find the most likely periods of each of the RR Lyraes.

3.2 RR Lyrae Properties

Our measured RR Lyrae properties are provided in Table 1, while their light curves are presented in Figure 5. We compare our RR Lyrae properties with those of Cohen et al. (2011). The amplitudes of the RR Lyrae light curves in this study are slightly, but insignificantly (0.02 ± 0.08 mags) larger than in Cohen et al. (2011). Most periods are comparable to 0.005 of a day or less, apart from two notable exceptions: V5 (this paper: 0.4259 d; Cohen: 0.7420 d) and V6 (0.3462 d; 0.5230 d). The data for V5 and V6 folded on the Cohen (2011) period estimates do not provide a believable light curve from our data, while our own period estimates in both cases provide very tight light curves. It is also the case that from visual inspection of Figure 4 from the Cohen et al. (2011) paper that these two stars, especially V5, are the 'worst' fitting of all their RR Lyrae templates and are also flagged as the RRab/c classification as being 'uncertain'. Running the same ANOVA period-finding method using observational RR Lyrae data from Cohen et al. (2011) finds the likely periods to be less than 0.003 d different from our findings. It is probable that our longer time baseline (≈9 months) and more staggered and random phase coverage provides a better dataset to determine periods accurately, without

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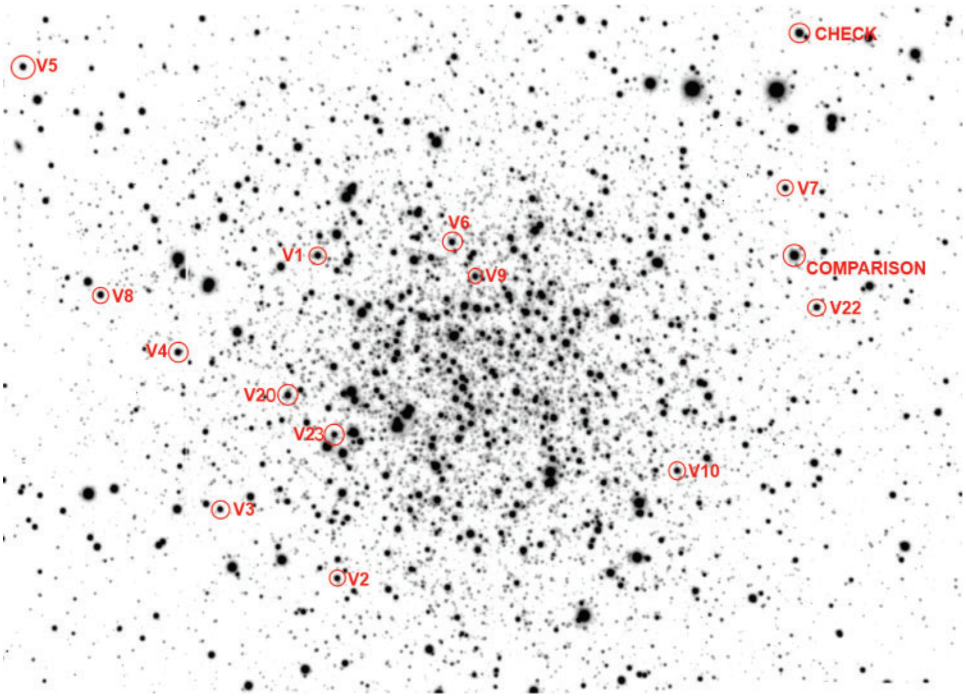

Figure 3 Finder chart constructed from V-band images used in this study. NE is at top left.

Table 1. RR Lyrae properties

ID	Period (days)	m_v^a (mag)	$(V-I)^b$ (mag)	Type[c] (mag)	A_v
V1	0.4583	16.26	0.58	RRc/1	0.44
V2	0.4116	16.44	0.38	RRc/1	0.62
V3	0.7545	16.51	0.56	RRab/0	0.82
V4	0.3490	16.49	0.32	RRc/1	0.52
V5	0.4259	16.54	0.59	RRc/1	0.44
V6	0.3462	16.35	0.54	RRc/1	0.44
V7	0.4101	16.46	0.57	RRc/1	0.48
V8	0.4152	16.51	0.44	RRc/1	0.56
V9	0.3402	16.16	0.55	RRc/1	0.38
V10	0.3486	16.36	0.38	RRc/1	0.52
V20	0.9144	16.22	0.56	RRab/0	0.40
V22	0.3191	16.42	0.45	RRc/1	0.12

[a] $m_v = (m_{min} + m_{max})/2$.
[b] $m_v - m_i$ where m_i is defined similarly to m_v.
[c] Classification schema of Bailey (1902)/more recent classification defined by Alcock et al. (2000).

assumption, than the short time baseline ($\approx$5 days) of Cohen et al. (2011), despite the lower precision of our photometry. There is no question that the profile-fitting method in Cohen et al. (2011) would be the superior method, but only if the data has relatively complete coverage over phase. It is also noted that V1 has a unusually high period for an RRc type RR Lyrae of 0.4583 d. From visual inspection as well as multiple numerical period finding methods using data from this paper and Cohen et al. (2011), both datasets separately present an equally likely period at 0.3141 d. However, by combining both available sets of data, after correcting for differences in mean magnitude, the period of 0.4583 d is by far the most likely from both visual and numerical methods.

Our mean V magnitudes are on average 0.056 mags brighter than those of Cohen et al. (2011), which may plausibly be due to leakage of light from other stars into our measurements due to the aperture photometry method used compared to their point-spread function method. We were limited to using aperture photometry due to the nature of this study, which is outlined in more detail in Section 4. This is, however, a relatively small systematic deviation and could also be just as easily explained by a combination of other factors such as differences in standard star calibrations or sky background estimates between the two studies, among other issues, as the RR Lyraes in this relatively diffuse globular cluster, apart from V9, are significantly separated from other surrounding stars.

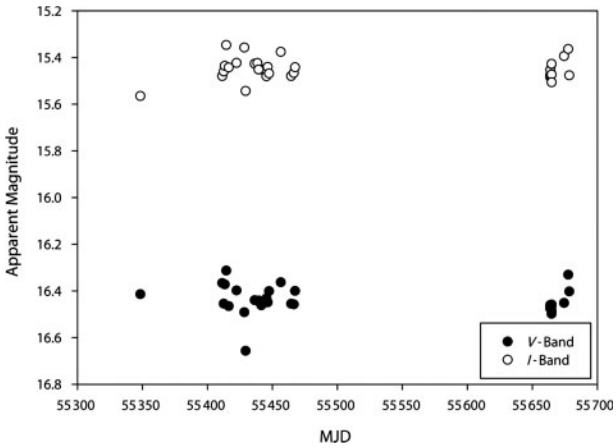

Figure 4 V- and I-band apparent magnitude of V23 over entire observing season. The points on the graph are approximately the size of the standard deviation of the comp-check magnitudes.

On the basis of the difference in period and also the obvious sinusoidal shape of the light curve, we reclassify V5 as an RRc type, while V6 retains its original RRc classification, although its period is now more aligned with the RRc average in this cluster. Combining our updated and new data with the previous Cohen et al. (2011) data, we confirm that the *P*ab stars have unusually long periods, in this case, $\langle Pab \rangle = 0.86$ d, while $\langle Pc \rangle = 0.383$, as well as confirming the classification of Oosterhoff type II with a high ratio of $n(c)/n(ab + c) = 0.833$.

3.3 Interstellar Reddening, Extinction and Distance

Apart from V9, which was determined to have significant light contamination from nearby stars, all the other variables were acceptably free from contamination. Theoretical RR Lyrae period-luminosity-metallicity relations (Catelan et al. 2004) were fitted to the V and I band data by introducing a constant representing the apparent magnitude, m, using a manual least squares minimization method.

$$M_v = 1.455 + 0.277 \log Z$$
$$M_i = 0.4711 - 1.1318 \log P + 0.2053 \log Z$$

Z was derived from the [Fe/H] $= -1.98$ from Harris (1996 (2010 edition)). From these fits, $(m - M)_v = 15.997 \pm 0.032$ and $(m - M)_i = 15.808 \pm 0.044$ were determined, where the errors were determined from the rms standard error of the fit. This provides a colour excess of $E(V - I) = 0.189$, implying an $E(B - V) = 0.15 \pm 0.04$, and an A_v of 0.47 ± 0.13 mags assuming a standard reddening law with $R = 3.1$. This compares well with the most recent estimates of $E(B - V) = 0.11 \pm 0.02$ (Schelgel et al. 1998), $E(B - V) = 0.09 \pm 0.01$ (Cohen et al. 2011) and the less certain $E(B - V) = 0.06 \pm 0.02$ (Sarajendi & De Costa 1991) and $E(B - V) = 0.1$ (Marconi et al. 2001). This leads to a distance estimate to NGC 6101 of $(m - M)_v = 16.00 \pm 0.03$, $(m - M - A_v) = 15.53 \pm 0.14$ or 12.8 ± 0.8 kpc which compares reasonably with the Cohen et al. (2011) estimation of $(m - M) = 16.00 \pm 0.03$, as well as $(m - M) = 16.07 \pm 0.1$ from Harris (1996).

3.4 New Variable, V23

The other new variable identified, V23, is of inconclusive type. Both ANOVA and phase-dispersion minimization methods did not find any plausible periodicity. Its variability, rms of 0.07 mags in V, as shown in Figure 4, is significantly higher than the comp-check rms stability of 0.01 mags. Its mean de-reddened $(V - I)$ colour of 0.95 and similar magnitude of 16.48 to the RR Lyraes, places it quite firmly on the RGB implying that it might be a long-period, small-amplitude red variable, although it is not positioned at its expected location near the tip of the RGB, or potentially an eclipsing binary considering the inability to find any periodicity over our 9-month time base.

4 Educational Aspects

This research was carried out within the scope of the educational Space to Grow project, an Australian Research Council Linkage Grant funded over three years. The project is supported by four industry partners. These include the Catholic Schools Offices of Bathurst and Parramatta (27 schools), the NSW Department of Education Western Region (11 schools) and the Las Cumbres Observatory Global Telescope network. A major aim of this project is to use astronomy as a vehicle to engage students in real science at school. In particular, students and teachers are provided with the opportunity to obtain and use real scientific data from the two 2-metre Faulkes Telescopes run by LCOGT.net. It is intended that the science that is done in class becomes publishable in the mainstream astronomical literature, which is evidenced by our previous publication involving high-school students on a little-studied planetary nebula (Frew et al. 2011) The Space to Grow Project also encompasses an educational research and development component designed to investigate the impact of the approaches adopted on students and teachers. Preliminary results obtained from the educational research reveal that students are engaged and excited by this approach to open inquiry in astronomy research.

Most of the measurement and interpretation work on NGC 6101 was carried out by two Year 11 students (JC and TL) as an independent research project for assessment led by MF and supervised by their teacher SW. The only parts of this paper that were not significantly undertaken by the students were the initial acquisition and reduction of data from the telescopes, the determination of RRa/bc Lyrae types, the Oosterhoff classification, the discussion of V23 and the final writing of the paper. The initial first draft of this paper was also constructed by the students. The draft was later condensed and moulded into the more formal scientific structure required.

The high school context was also the source of the limitation of only using aperture photometry on the cluster. There is no adequate free solution to perform optimal/PSF photometry within a Windows or Mac environment. While this approach worked well for this relatively diffuse globular cluster, we intend to get future students to work on other denser globular clusters. This will require the development of a free cross-platform optimal/PSF photometry package capable of being run on computers normally found in schools and which suffer from being 'tightly tied down' by IT administrators. These issues are currently being worked on.

5 Conclusion

In this paper we have observed the globular cluster NGC 6101 over a period of ≈9 months to adequately survey the RR Lyrae population in this cluster. Our data

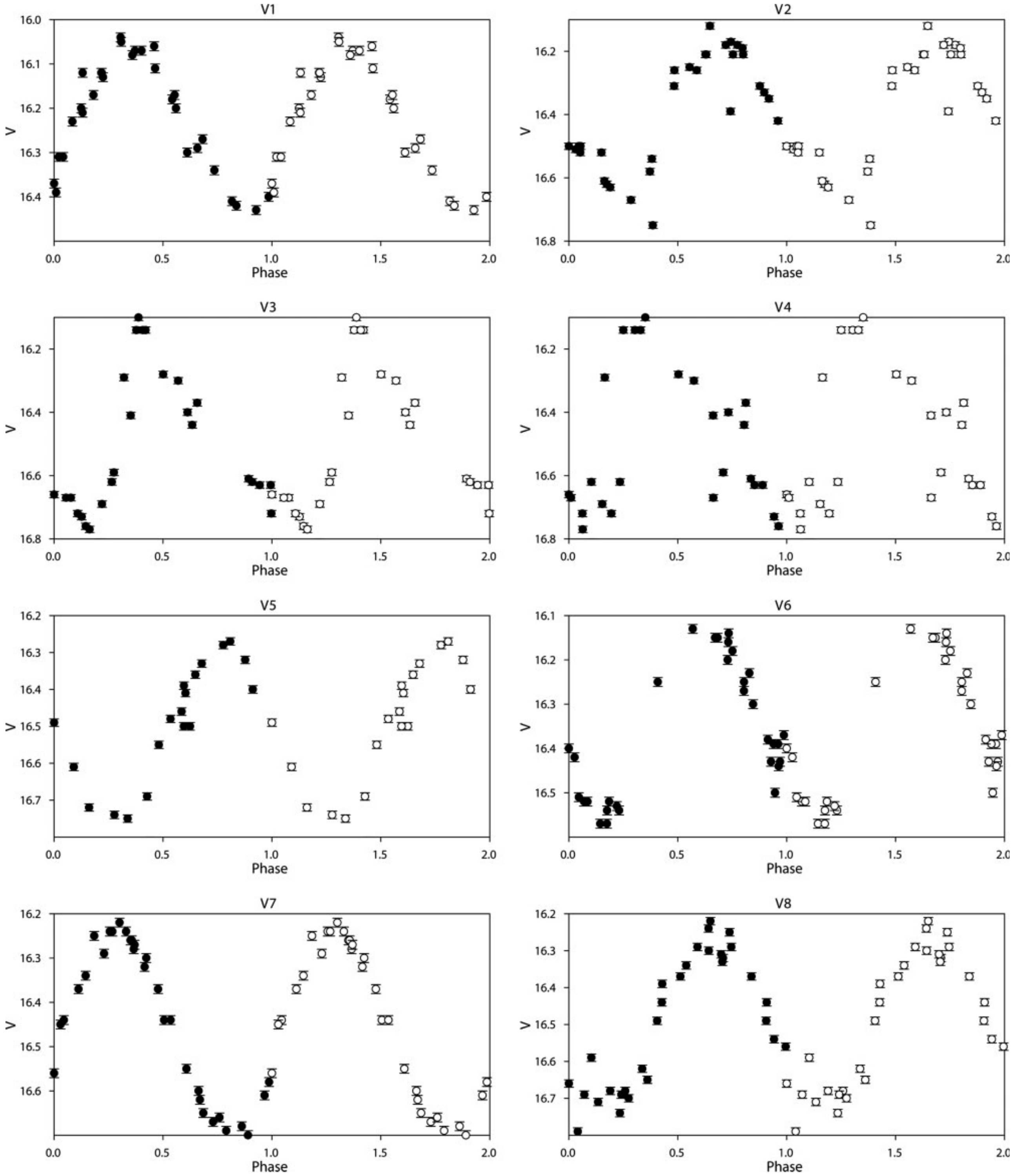

Figure 5 Light curves of observed RR Lyraes phase-plotted over two cycles on most likely period.

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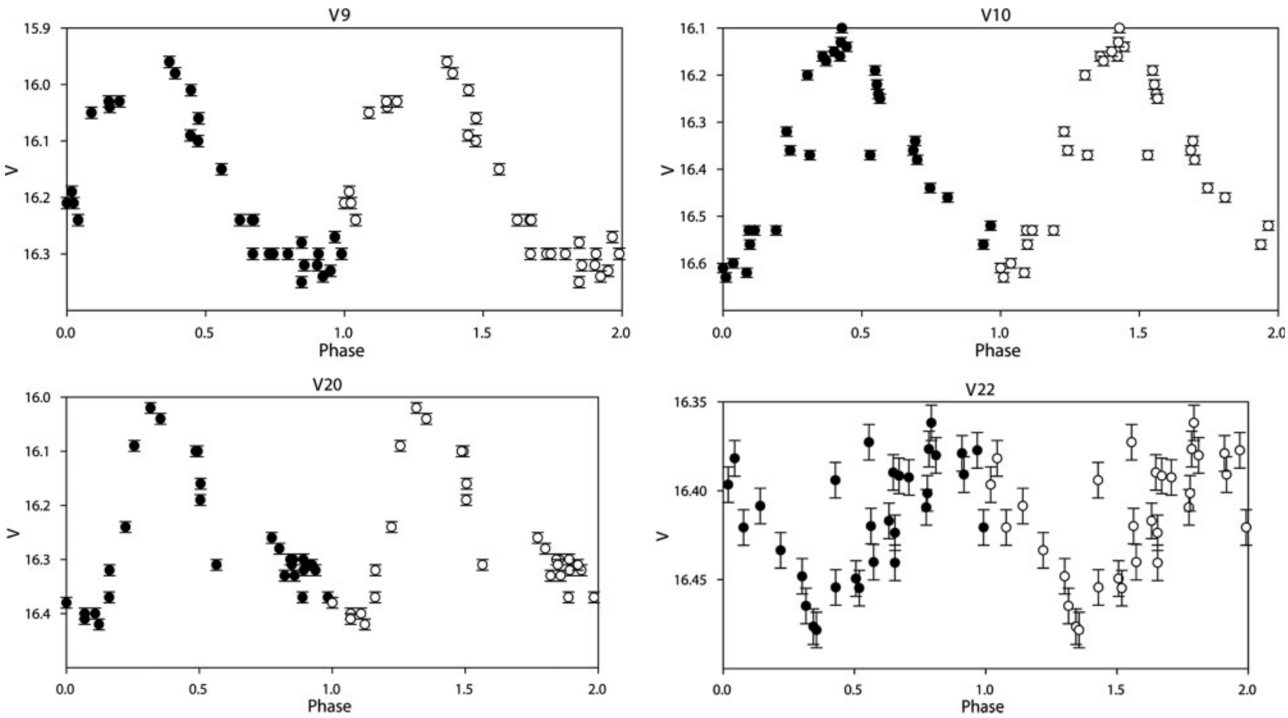

Figure 5 (*Continued*)

compliments and updates the study of Cohen et al. (2011), reclassifying one RR Lyrae and updating the periods of two RR Lyraes. We have also identified one new variable, potentially a small-amplitude semi-regular or irregular variable or eclipsing binary. As well as this we have arrived at an independent estimate of the reddening, $E(B-V)=0.15\pm0.04$, and distance, $(m-M)_v=16\pm0.03$, $(m-M-A_v)=15.53\pm0.14$ or 12.8 ± 0.8 kpc. The majority of the work in this project was undertaken by upper secondary school students involved in the Space to Grow astronomy education project in Australia.

Acknowledgments

MF acknowledges receipt of MQRES PhD scholarship from Macquarie University. Appreciation is given to the freely available software used in this project: Subaru Image Processor Makali'i (`http://makalii.mtk.nao.ac.jp/`) and Munwin (`http://c-munipack.sourceforge.net/`) as well as the non-free Peranso period-finding software (`http://www.peranso.com/`).

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