

Observing Globular Cluster RR Lyrae Variables with the BYU West Mountain Observatory

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Abstract We have utilized the 0.9-meter telescope of the Brigham Young University West Mountain Observatory to secure data on six northern hemisphere globular clusters. Here we present representative observations of RR Lyrae stars located in these clusters, including light curves. We compare light curves produced using both DAOPHOT and ISIS software packages. Light curve fitting is done with FITLC. We find that for well-separated stars, DAOPHOT and ISIS provide comparable results. However, for stars within the cluster core, ISIS provides superior results. These improved techniques will allow us to better measure the properties of cluster variable stars.

1. Introduction

Globular clusters (GCs) provide an important environment for studying RR Lyrae (RRL) variable stars. Our ability to maximize information in these data rests upon our ability to adequately measure photometry for the RRL cluster members. The stars in a typical GC field are crowded, at times making photometry difficult. This is especially true for stars in the cluster core. Good photometry of stars in a GC often requires the use of point-spread function (PSF) fitting techniques, though at times even this may be inadequate if the field is especially crowded, like in the overly-crowded GC core. When the stars are especially crowded, image subtraction methods may provide superior results.

This report includes a summary of results that have been presented at several venues in the past six months. These include the 2015 October conference in Hungary on High-precision Studies of RR Lyrae Stars (Jeffery *et al.* 2016), the 2015 November AAVSO Annual Meeting in Massachusetts (Joner and Jeffery 2016), and the 2016 January Winter Meeting of the American Astronomical Society in Florida (Jeffery and Joner 2016).

In this report, we present representative results of new time-series observations of six northern hemisphere GCs, and compare light curves obtained using PSF fitting photometry and image subtraction methods. We fit light curves to the resulting data points using the template-fitting program FITLC (Sarajedini *et al.* 2009). The use of photometric techniques appropriate to different levels of crowding will allow us to obtain better light curves for GC RRLs, resulting in a better determination of the properties of the cluster variable stars.

2. Observations

We have observed six northern GCs with the 0.9-meter telescope at the West Mountain Observatory (WMO) that is owned and operated by Brigham Young University (BYU). WMO is located approximately 23 km southwest of the main BYU campus in Provo, Utah. The observations were done using a Fairchild 3041-UV 2048 × 2048 CCD. Using this CCD on the 0.9-meter results in a plate scale of 0.61 arcseconds per pixel, and a field of view of 20.8 arcminutes in each dimension.

The GCs we observed are: NGC 5272 (M3), NGC 5466, NGC 5904 (M5), NGC 6205 (M13), NGC 6341 (M92), and NGC 7078 (M15). Observations for five GCs (all but NGC 5466) were secured in a standard UBVR filter set during the 2012 observing season; NGC 5466 was observed in 2014 in BVR filters. For each cluster we have between 69 and 229 individual observations, resulting in well-sampled light curves. We reduced the raw data frames using standard procedures in the IRAF CCDRED package for flat, dark, zero, and overscan corrections.

We have summarized our observations in Table 1. Target stars in these clusters are previously identified RRLs from the catalog of Clement *et al.* (2001). Comparison stars across the field of view were used for differential photometry. These stars were chosen based on similar brightness to the variables and were verified to be non-variable over the entire baseline of observations.

Table 1. Log of Cluster Observations.

<i>Cluster</i>	<i>Number of V Observations</i>	<i>Dates Observed</i>
NGC 5272 (M3)	219	Apr–Aug 2012
NGC 5466	69	Mar–Jul 2014
NGC 5904 (M5)	170	Apr–Jul 2012
NGC 6205 (M13)	229	Apr–Sep 2012
NGC 6341 (M92)	217	Mar–Aug 2012
NGC 7078 (M15)	91	Jun–Sep 2012

Note: 1 Observation sequences were completed in UBVR filters, except in the case of NGC 5466 which was observed in BVR filters. Only the number of V images is listed here; the number of images in the other filters is comparable.

3. Photometry and light curves

We measured photometry to construct light curves using two different methods: PSF-fitting methods using DAOPHOT/ALLSTAR (Stetson 1987) and image subtraction methods employed by the ISIS software suite (Alard 2000). Here we describe each method and compare the resulting light curves.

3.1. DAOPHOT

We utilized DAOPHOT to obtain instrumental magnitudes for all stars in the globular cluster frames. Briefly, tasks within DAOPHOT were used to do the following: find coordinates for all stars on the frame (using DAOFIND); perform aperture photometry to determine instrumental magnitude zeropoints and calculate sky values; construct a spatially varying PSF for each image using well separated stars; and simultaneously fit (using ALLSTAR) the PSF to each star on the frame. The result was instrumental magnitudes for all targets and comparison stars.

The first results shown here are for the RRLs in the moderately crowded fields in the cluster NGC 5466. The well-known anomalous Cepheid, BL Boo, is one of the brighter target objects in this field. In Figure 1, we show results for BVR photometry obtained for BL Boo using DAOPHOT. Even though the results for some of the data points were affected by deteriorating observing conditions (shown by larger error bars), it is clear that DAOPHOT produces well-defined light curves for stars with this level of crowding.

In order to demonstrate that DAOPHOT analysis is generally acceptable for moderately crowded fields like those found in NGC 5466, we show results for nine of the 20 RRL stars listed for the cluster in the catalog of Clement *et al.* (2001). The BVR plots for these representative variables are displayed in Figure 2. Once again, it is clear that analysis with DAOPHOT is adequate for stars in fields outside the GC core.

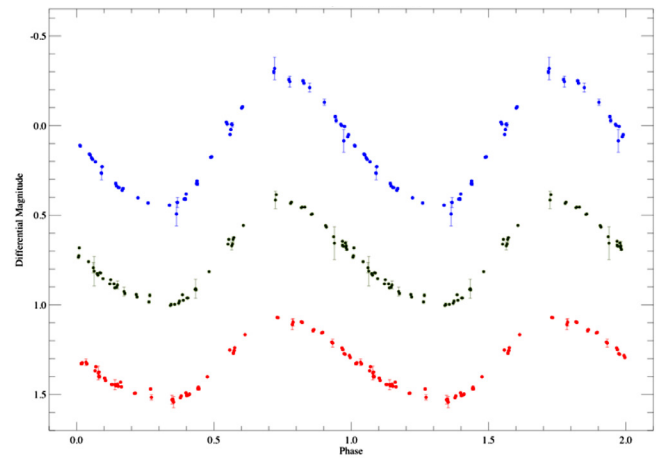


Figure 1. DAOPHOT B (top (blue) plot), V (middle (green) plot) and R (lower (red) plot) photometry for the anomalous Cepheid, BL Boo, located in NGC 5466. The points with larger error bars were secured on nights with rapidly changing observing conditions. All of the points are shown with error bars, but in most cases these are comparable to the size of the points that are used in the plot. Clearly, DAOPHOT PSF-fitting provides photometry for a well-defined light curve for this level of crowding.

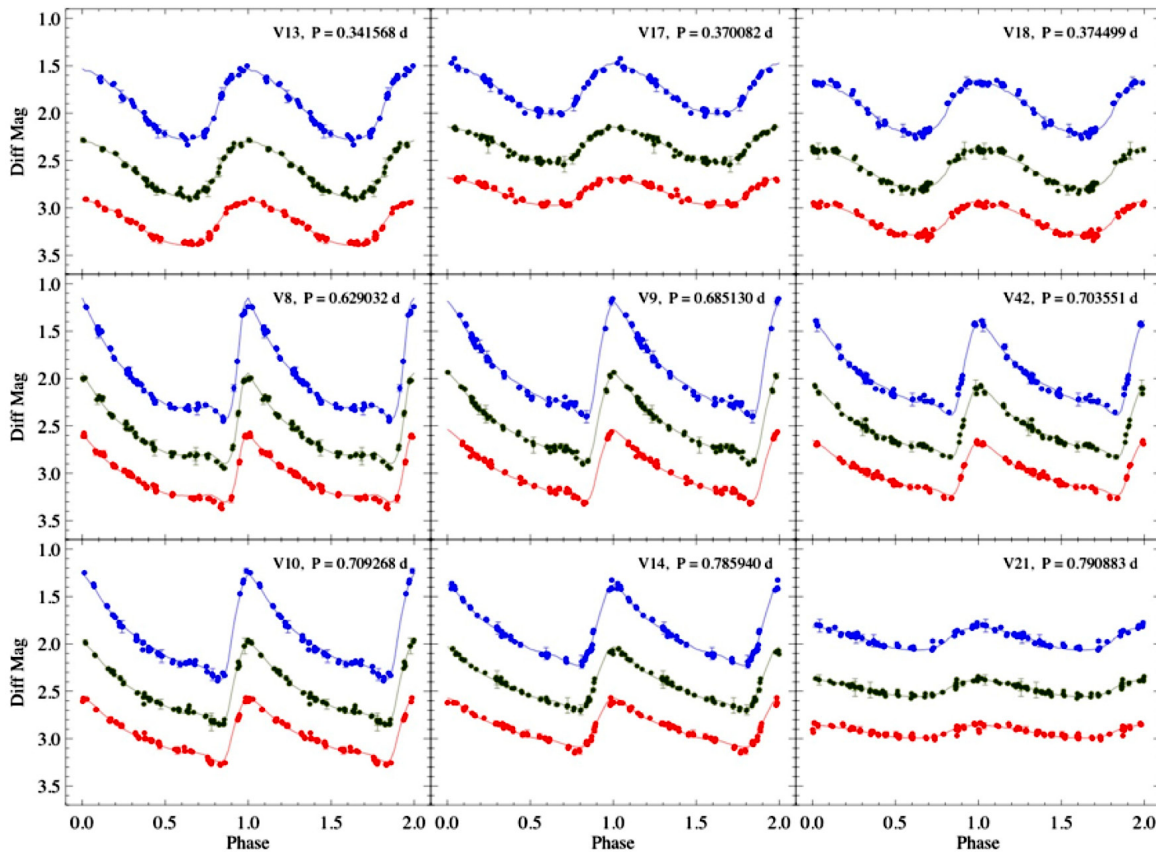


Figure 2. DAOPHOT B (upper (blue) plots), V (middle (green) plots), and R (lower (red) plots) photometry for nine RRL stars in the cluster NGC 5466. All of the points are plotted with error bars but in most cases these are smaller than the size of the individual points. In each case, the curve was fit and the period found using FITLC. The photometry determined using DAOPHOT is consistent from night to night and the resulting light curves are adequately sampled in all filters.

3.2. ISIS

We also obtained light curves of cluster variable stars by measuring the differential flux of the target stars using the image subtraction routines in the ISIS software (Alard 2000). The ISIS software package is freely available for download from Alard's website.

The first step in using ISIS is to align all of the images for each field. Next, we selected the best GC images, and used ISIS to create a reference image for each target cluster. Each individual image is subsequently subtracted from this reference image. This results in non-variable stars subtracting out, leaving only flux from the variable stars. The result of this process is a less contaminated measurement of the flux from the variable stars in a field.

Because ISIS determines differential flux (not magnitude) values, we converted these to differential magnitude values using the method outlined in Szekely *et al.* (2007). To determine this relationship, we used the high-amplitude, well-separated star V11 in the cluster M3. We show this relationship in Figure 3. The red line is the calculated fit (found via a standard linear, least squares regression). For comparison, in Figure 3 we also show data for another well-separated star in M3, V37. Note the fit to the data for both stars is in excellent agreement, increasing our confidence in this transformation.

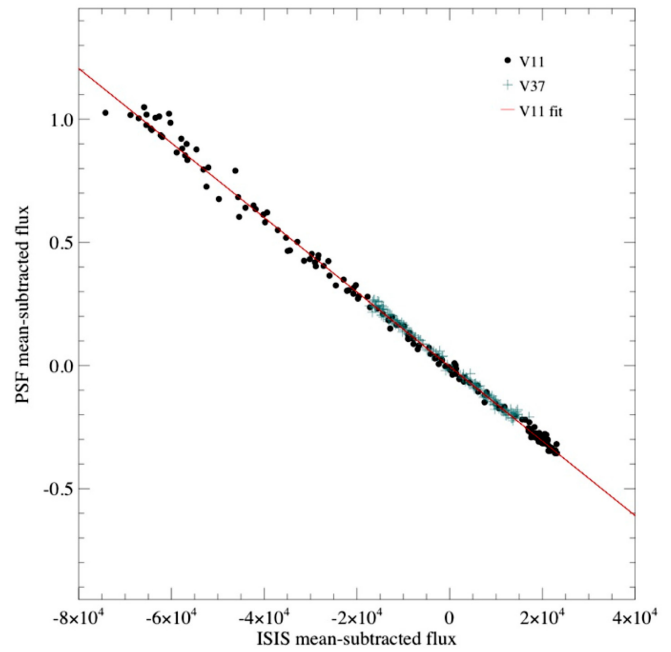


Figure 3. The relationship between mean-subtracted flux values from ISIS and DAOPHOT. We determined the fit (line) using a well-separated, high amplitude star (V11 in the cluster M3). For comparison, we also show data for another well-separated star in M3, V37 (plus symbols). We note the excellent agreement of the data for the star to the fit from V11.

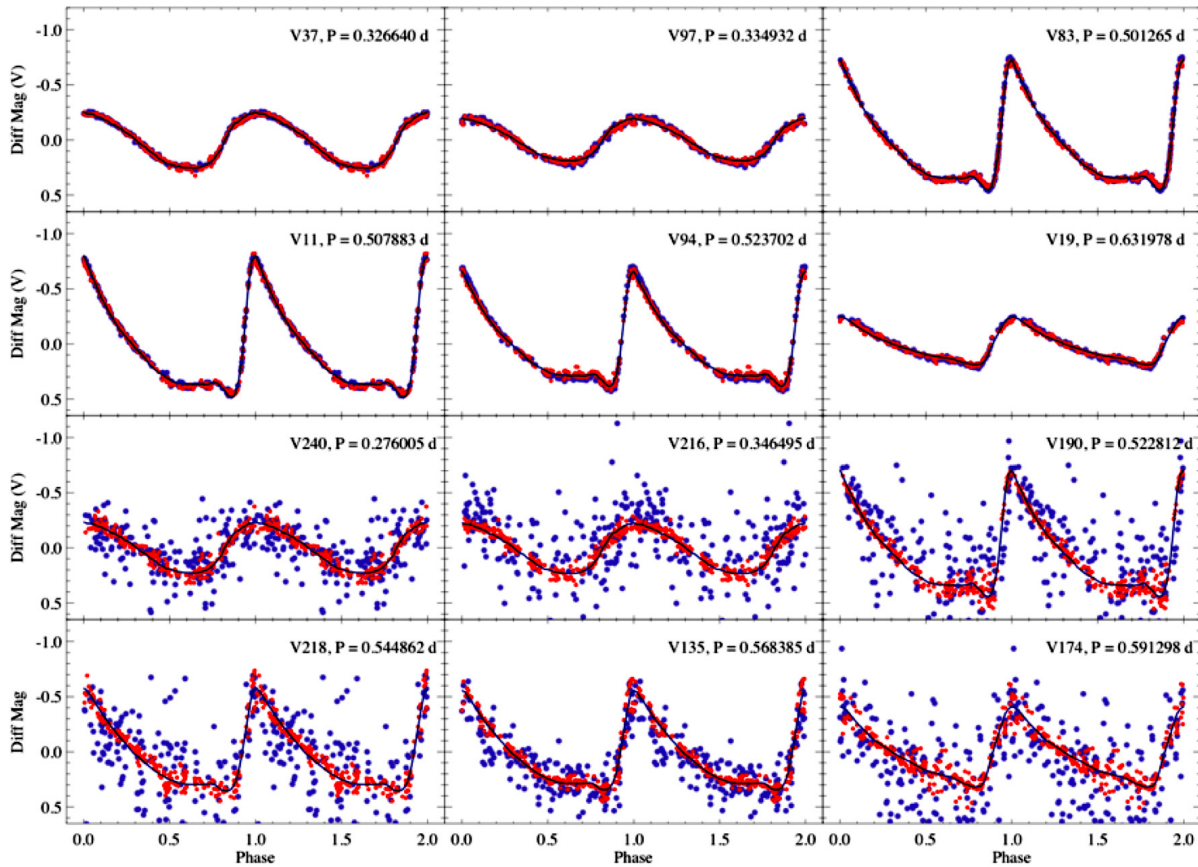


Figure 4. Light curves for 12 RRL stars in M3. Six RRLs (V11, V19, V37, V83, V94, and V97) shown in the top two rows are well separated from nearby neighbors due to locations in the outer portion of the GC. The other six RRLs (V135, V174, V190, V216, V218, and V240) are located in the crowded cluster core. DAOPHOT (dark (blue) dots) and ISIS (light (red) dots) photometry are plotted for comparison, along with the best fit template and period, found by FITLC. The results obtained from ISIS photometry are clearly superior in the crowded cluster core.

Once we determined the relationship between output values from ISIS and DAOPHOT, we converted all ISIS differential flux values to differential magnitudes. This allowed for direct comparison between the two, as well as light curves that can be analyzed. We used FITLC (Sarajedini *et al.* 2009) to fit an RRL template to determine periods. Template fitting was done on transformed ISIS light curves.

In Figure 4, we compare light curves determined from DAOPHOT and ISIS methods for 12 stars in M3: six RRLs (V11, V19, V37, V83, V94, and V97) are well-separated from nearby neighbors in the cluster halo and the other six RRLs (V135, V174, V190, V216, V218, and V240) are in the crowded cluster core. As can be seen in this figure, for stars without nearby companions, DAOPHOT and ISIS provide comparable results. However, the light curves found using ISIS are superior in the crowded cluster core. The periods listed in Figure 4 are those found by FITLC.

4. Summary

We have presented representative observations of GC RRLs secured with the WMO 0.9-m telescope. We have constructed light curves using both DAOPHOT PSF-fitting photometry routines and image subtraction methods employed by the ISIS software package. For stars that are well separated from other stars, we show that DAOPHOT and ISIS provide comparable results. For stars in the crowded cluster core, we demonstrate that superior light curves are obtained from ISIS analysis. Using these methods, we are able to determine improved periods for RRL stars in the crowded cluster core using the template-fitting

program FITLC. Such methods hold great promise for studying all RRL stars in various GCs, including those found in the crowded cluster core.

5. Acknowledgements

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