NEW SX PHOENICIS VARIABLES IN THE GLOBULAR CLUSTER NGC 4833
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ABSTRACT
We report the discovery of 6 SX Phoenicis stars in the southern globular cluster NGC 4833. Images were obtained from January through June 2011 with the Southeastern Association for Research in Astronomy 0.6 meter telescope located at Cerro Tololo Interamerican Observatory. The image subtraction method of Alard & Lupton (1998) was used to search for variable stars in the cluster. We confirmed 17 previously cataloged variables by Demers & Wehlau (1977). In addition to the previously known variables we have identified 10 new variables. Of the total number of confirmed variables in our 10 × 10 arcmin² field, we classified 10 RRab variables, with a mean period of 0.69591 days, 7 RRc, with a mean period of 0.39555 days, 2 possible RRe variables with a mean period of 0.30950 days, a W Ursae Majoris contact binary, an Algol-type binary, and the 6 SX Phoenicis stars with a mean period of 0.05847 days. The periods, relative numbers of RRab and RRc variables, and Bailey diagram are indicative of the cluster being of the Oosterhoff type II. We present the phased-light curves, periods of previously known variables and the periods and classifications of the newly discovered variables, and their location on the color-magnitude diagram.

Subject headings: stars: variables: general–Galaxy: globular clusters: individual: NGC 4833

1. INTRODUCTION
NGC 4833 is a southern globular cluster lying near the Galactic plane in the constellation Musca. Its variable stars have not been studied in detail for nearly 35 years since observations by Demers & Wehlau (1977). The first survey of variable stars in the cluster’s vicinity was done by Bailey (1924) who found two variables, both of which are likely not cluster members. Later studies revealed a total of 16 variables in the vicinity of the cluster (Wright 1941; Sawyer-Hogg 1973). Among these were the two variables found by Bailey with most of the remaining being cluster variables, known today as RR Lyrae variables. Using photographic plates Demers & Wehlau (1977) did B and V photometry of the cluster identifying 24 variables and determined accurate periods for 15 RR Lyrae variables. They concluded that the cluster was Oosterhoff Type II (Oosterhoff 1939). The most recent study was Melbourne et al. (2000). They investigated extinction near NGC 4833 and determined the positions of the RR Lyrae variables on a color-magnitude diagram but did not do time-series photometry. NGC 4833 is 6.6 Kpc from the Sun, has a core radius of 1.0′, and a half light radius of 2.41′ which make it a relatively easy target for searching for and investigating its variable stars (Harris 1996).

Given the lack of recent detailed study of the variables in NGC 4833 we added the cluster to our continuing program to study in detail a number of southern globular star clusters (Conroy et al. 2012, Toddy et al. 2012). With the combination of CCD images, an observation window spanning more than 4 months, and an image subtraction package developed by Alard (2000), we are able to detect, analyze variable stars, and produce unprecedented high-quality light curves and periods for each variable. In this study we present the preliminary results of our observations of NGC 4833 including a color-magnitude diagram, as well as a Bailey diagram, complete light curves, and periods for 27 variables, with 10 of them being newly identified.

2. OBSERVATIONS AND ANALYSIS
Images of NGC 4833 were obtained during 14 nights between 30 January and 25 June, 2011, using the Southeastern Association for Research in Astronomy (SARA) 0.6 meter telescope located at Cerro Tololo Interamerican Observatory. In all, nearly 1700 images were obtained in the V-band. Also, multicolor sequences were done on 9 March, 1, 3, and 6 May, 2011, as a VRI sequence on 9 March, and a BVRI sequence on 1, 3, and 6 May. An Apogee Alta E6 camera was used for the observations with a 1024×1024 pixel Kodak KAF1001E chip, a gain of 1.5 electron per ADU count, and an RMS noise of 8.9 electrons. We used 1×1 binning resulting in an image scale of 0.61″/px resulting in a 10×10 arcmin² field of view. On all nights of observation, 120 second exposures were taken using a Bessel V filter. The exposure time allowed us to detect dimmer variables but caused many of the brighter stars in the field to be overexposed. Typical seeing ranged between 1.2 and 1.7″ in the V-band.

All images were debiased, flat-fielded, dark subtracted, and cleaned of hot, cold, and bad pixels. Images were then analyzed using the ISIS2.2 package (Alard & Lupton 1998, Alard 2000). The package works by convolving the reference image shown in Figure 1, composed of a combination of the highest quality images obtained, to the point spread function of each individual image, then subtracting each image from the reference image to determine if any change in intensity has occurred. A resulting variable image identifies possible variables and is shown in Figure 2. A more detailed discussion of the method and how we used it is given elsewhere in this volume by Toddy et al. (2012).
Fig. 1.— The reference image used for all nights of the analysis/image subtraction. This image is a combination of the best seeing images, with the combined seeing near 1.3′′. Note that brightest stars in the image are overexposed.

TABLE 1

| Variable Type | Count | Period (days) |
|---------------|-------|---------------|
| RRab          | 10    | 0.69591       |
| RRc           | 7     | 0.39555       |
| RRe           | 2     | 0.30950       |
| Eclipsing     | 2     | 0.32431       |
| SX Phe        | 6     | 0.05847       |

Due to the more than 4-month observation span, we were able to determine the periods of most of the variables with periods less than 1 day to an accuracy of $10^{-5}$ days. Those variables exhibiting the Blažhko Effect were less accurate due to modulation of their light curves (Blažhko 1907, Smith 2004). Demers & Wehlau’s (1977) variables were identified visually and astrometrically and then confirmed by comparing their periods with our own. Several of the variables identified by Demers & Wehlau (1977) were outside the field of view of our images thus were not be observed. These include their variables V1, V2, V8 and V10. We were not able to produce time-series photometry of two other variables, V9 and V16. Though they were in our field of view they were overexposed giants.

3. RESULTS

Table 1 summarizes the results of our study. In total we detected 27 variables with 10 of them being newly identified. Of the variables that were in our field of view and listed by Demers & Welhau (1977) we were able to identify all but two. The two that we did not detect happened to be overexposed. Of the total we detected 6 were newly discovered SX Phoenicis variables, 19 RR Lyrae variables, and 2 eclipsing variables. Table 2 gives the properties of each of the variables. The SX Phoenicis variables are characterized by short periods and relatively low amplitudes. The mean period of the SX Phoenicis variables is 0.05847 days, with a minimum of 0.04425 days and a maximum of 0.07191 days along with V amplitudes ranging from 0.2 to 0.7 magnitudes. These amplitudes are only estimates given that many of the SX Phoenicis variables appear to be modulated and blended with other stars. NV5 was detected by ISIS only on 5 April. The others were detected on all of the nights. All of the SX Phoenicis stars were within the half-mass radius (2.4′) of the cluster as listed by Harris (1996). The phased light curves for the SX Phoenicis stars are shown in Figure 3.

Of the RR Lyrae variables identified in the cluster 10 were RRab variables, with a mean period of 0.69591 days, 7 were RRc variables, with a mean period of 0.39555 days, and variable V20 which may be a second overtone (RRe) variable previously noted by Demers & Wehlau (1977). But given V20's modulated light curve it may be a type RRd double-mode variable (Alcock et al. 1996, Bono et al. 1997). Our newly discovered variable stars include a W Ursae Majoris star (period of 0.3629 days), an RRab star (period of 0.8740 days), another second overtone (RRe) variable (period of 0.3179 days), and an Algol type binary star (period of 0.7231 days). In total we identified 10 new variables in the cluster. The phased light curves for these variables are shown in Figure 4. In addition to the ratio of RRab to RRc Lyrae variables the Bailey diagram presented in Figure 5 shows the cluster is of the Oosterhoff type II cluster. In this diagram the fitting formulae are from Zorotovic et al. (2010). Figure 5 also shows the two outlying RRe variables, indicated by the open triangles.

Color-magnitude diagrams (CMD) are useful in determining cluster membership. To verify cluster membership we produced a Color-magnitude diagram for NGC 4833 shown in Figure 6 with the various types of variable and...
Fig. 3.— 6 previously unknown SX Phoenicis stars were found. Their mean period is 0.05847 days.

Fig. 4.— Phased light curves for other variables with periods under a day.
Fig. 4.— (Continued) Phased light curves of all other variables with periods under 1 day. Newly discovered variables have been given the NV prefix.
stars indicated. To construct this diagram we combined 165 V band images, with an exposure of 120 seconds, and 175 R band images, with an exposure of 45 seconds. The images were obtained as part of a BVRI color sequence on 9 March, 1, 3, and 6 May, 2011. **DAOPHOT** was used to determine V and R magnitudes of the stars (Stetson 1987). In the CMD shown in Figure 6 RRab and RRc variables are indicated by the red and blue colored points, respectively. RRc variables tend to lie on the warmer (left) side of the instability strip whereas RRab variables are to the cooler (right) of the instability strip. Scatter in the variables is partly due to blending of the variables with other stars, our averaging of several hundred images before using **DAOPHOT**, and possible variable reddening in the direction of the cluster. We assumed fixed atmospheric extinction coefficients for each color and for all nights.

### TABLE 2

| V#  | RA(h,m,s)       | Dec(°,′,″) | P(d)  | V   | A_V | Type       |
|-----|-----------------|-----------|-------|-----|-----|------------|
| V1  | RY Musca, not in our field of view. |           |       |     |     |            |
| V2  | RZ Musca, not in our field of view. |           |       |     |     |            |
| V3  | 12 59 33.08, -70 51 13.8, 0.74449 | 15.1 0.63 | RRab  |
| V4  | 12 59 33.72, -70 51 58.4, 0.65550 | 15.3 1.20 | RRab  |
| V5  | 13 00 01.26, -70 53 17.7, 0.62942 | 15.3 0.90 | RRab  |
| V6  | 12 59 56.12, -70 50 10.5, 0.65395 | 15.6 1.10 | RRab  |
| V7  | 12 59 48.79, -70 52 21.5, 0.60842 | 15.4 1.10 | RRab  |
| V8  | Confirmed not to be variable.     |           |       |     |     |            |
| V9  | Overexposed long period variable. |           |       |     |     |            |
| V10 | Not in our field of view.         |           |       |     |     |            |
| V11 | Not in our field of view.         |           |       |     |     |            |
| V12 | 12 59 37.99, -70 52 15.1, 0.58970 | 15.4 0.69 | RRab  |
| V13 | 13 00 29.79, -70 52 56.1, 0.36788 | 15.4 0.49 | RRc   |
| V14 | 12 59 31.02, -70 53 07.3, 0.40841 | 15.3 0.39 | RRc   |
| V15 | 12 59 20.10, -70 53 25.6, 0.66730 | 15.1 0.85 | RRab  |
| V16 | Overexposed long period variable. |           |       |     |     |            |
| V17 | 12 59 43.96, -70 54 25.5, 0.39039 | 15.4 0.46 | RRc   |
| V18 | 12 59 28.19, -70 54 26.2, 0.42587 | 15.5 0.43 | RRc   |
| V19 | 12 59 05.94, -70 53 30.3, 0.37060 | 15.5 0.51 | RRc   |
| V20 | 12 59 08.10, -70 52 24.2, 0.30020 | 15.7 0.10 | RRc   |
| V21 | 12 59 50.90, -70 50 36.8, 0.39900 | 15.4 0.55 | RRc   |
| V22 | 12 59 45.08, -70 53 55.9, 0.85070 | 15.2 0.60 | RRab  |
| V23 | 12 59 44.72, -70 51 27.5, 0.40665 | 15.4 0.48 | RRc   |
| V24 | 12 59 36.67, -70 52 59.1, 0.62570 | 15.5 1.05 | RRab  |
| NV1 | 12 58 55.31, -70 51 46.4, 0.72300 | 18.6 0.00 | EA    |
| NV2 | 12 59 02.68, -70 52 52.3, 0.31790 | 15.6 0.16 | RRc   |
| NV3 | 12 59 13.65, -70 52 10.3, 0.80979 | 17.8 0.62 | SXPhc  |
| NV4 | 12 59 21.20, -70 53 26.8, 0.87395 | 15.2 0.28 | RRab  |
| NV5 | 12 59 35.32, -70 52 41.9, 0.05965 | 15.5 0.10 | SXPhc  |
| NV6 | 12 59 42.52, -70 53 04.6, 0.04425 | 18.3 0.30 | SXPhc  |
| NV7 | 12 59 47.92, -70 52 52.2, 0.03332 | 16.5 0.19 | SXPhc  |
| NV8 | 12 59 55.04, -70 52 24.6, 0.07067 | 17.2 0.70 | SXPhc  |
| NV9 | 12 59 57.66, -70 54 30.6, 0.07191 | 16.2 0.33 | SXPhc  |
| NV10| 13 00 25.08, -70 49 16.3, 0.36287 | 16.0 0.15 | EC     |

Of the RR Lyrae variables only one, V15, appears to be a blend. V15 is shown in Figure 6 as the hollow red square to the right of the instability strip. Other than this errant variable the remainder appear near the instability strip. In addition to blending there is significant extinction across the cluster. The E(B-V) is listed as 0.32 and Melbourne et al. (2000) found that this varies depending on location. Because of this variable interstellar extinction some scatter is introduced into our mean magnitudes of the RR Lyrae variables.

The SX Phoenicis variables all lie to the left of the giant branch. After close inspection of the images all but one of our SX Phoenicis variables appeared to be blended with stars of equal or greater brightness. Further inspection of Hubble Space Telescope images confirmed this. Variables NV4 and NV5 appear to be blended with giant stars whereas NV7, NV8, and NV9 are blended with stars of similar brightness to themselves. NV6 is the only SX Phoenicis variable that does not appear to be blended with a relatively bright or comparable bright star.
4. CONCLUSIONS

For nearly 5 months from late January through June of 2011 we observed the globular cluster NGC 4833 using the SARA 0.6 meter telescope at CTIO. Using the image subtraction software ISIS we were able to find precise periods of 17 previously known variables and 10 newly discovered variables stars. Of these new discoveries we found 6 SX Phoenicis variables. The other 4 newly discovered variables were 2 eclipsing, one RRab, and one apparent RRc. In total, we classified 10 of the variables as type RRab, with a mean period of 0.69591 days, 7 as type RRc with a mean period of 0.39555 days, perhaps 2 lower amplitude type RR, with a mean period of 0.30950 days, and 2 eclipsing binaries, with a mean period of 0.3243 days. Both the Bailey diagram and ratio of $N_c/N_{ab}$ are consistent with the cluster being of type Oosterhoff Type II.

We thank C. Alard for making ISIS 2.2 publicly available. This project was funded in part by the Butler Institute for Research and Scholarship. The authors also thank F. Levinson for a generous gift enabling Butler University’s membership in the SARA consortium.

REFERENCES

Alard, C., & Lupton, R. H. 1998, ApJ, 503, 325
Alard, C. 2000, A&AS, 144, 363
Alcock, C., Allsman, R. A., Axelrod, T. S., et al. 1996, AJ, 111, 1146
Bailey, S. I. 1924, Harvard College Observatory Bulletin 801, pp.7-8
Blažko, S. 1907, Astronomische Nachrichten, 175, 325
Bono, G., Caputo, F., Cassisi, S., Incerpi, R., & Marconi, M. 1997, ApJ, 483, 811
Conroy, K. E., Darragh, A. N., Liu, Z. J. & Murphy, B. W. 2012, JSARA, 5, 34
Demers, S., & Wehlau, A. 1977, AJ, 82, 620
Harris, W. E. 1996, AJ, 112, 1487
Melbourne, J., Sarajedini, A., Layden, A., & Martins, D. H. 2000, AJ, 120, 3127
Oosterhoff, P. T. 1939, The Observatory, 62, 104
Smith, H. A. 2004, RR Lyrae Stars, by Horace A. Smith, ISBN 0521548179. Cambridge, UK: Cambridge University Press
Stetson, P. B. 1987, PASP, 99, 191
Wright, F. W. 1941, Harvard College Observatory Bulletin, 916, 3
Toddy, J. E., Johnson, E. W., Darragh, A. N., & Murphy, B. W. 2012, JSARA, 6
Zorotovic, M., Catelan, M., Smith, H. A., et al. 2010, AJ, 139, 357