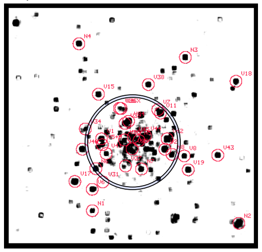
Search for Long-Period Variables on the Edges of the Hercules Globular Cluster, M13

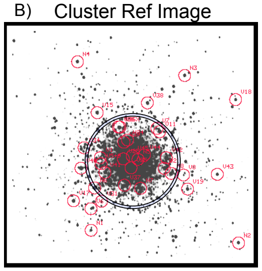
Keith McBride & Andrew Layden

Dept. of Physics & Astronomy, BGSU (Independent Study)

A) Variables



B) Cluster Ref Image



A) The variables stars detected through Image Subtraction (ISIS) appear as the black shapes in this inverted image. Those stars outside of the circle drawn are the scope of this research. Each star that is a known variable has a label of "V#" and there are eight that have been labeled "N#" as new variables, not found in previous research.

B) The inverted reference or Master image for the *V*-band shows all stars detected in the globular cluster. The same labels appear for known and new variables.

Abstract

In order to discover and confirm Long-Period Variable (LPV) stars in the M13 Globular Cluster, we analyzed *V*- and *I*-band images taken over a timeframe of 5 years (2006-2011). Analysis of these images were conducted in a UNIX environment utilizing IRAF, ISIS, and SM. The results include 35 variable stars detected, and as many as 6 new LPV's discovered. The type of variability was deduced from light curves and plotting on the color-magnitude diagram (from DAOPHOT). Many of the detected variables and their periods are consistent with previous research, however our data suggest different periods or even no variability at all for a few stars. This research presents the results of those variables on the edges of the cluster, >25 arcsec from the center. For the new suspected LPV's, Right Ascension (RA) and Declination (DEC) coordinates were determined through 2MASS image files. Overall, this research helps provide information for theoretical modeling of pulsation instability.

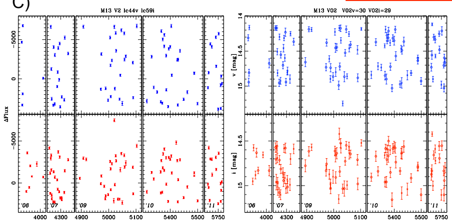
IRAF

Images were taken using the BGSU 0.5m telescope with Apogee Ap6e CCD camera in both the *V* and *I*-bands for a total of 8 images taken per observation epoch. In addition, each of these 8 images is offset slightly compared to the others so that when they are combined and referenced, any consistently bad pixels are removed, increasing the signal to noise ratio for each night. This process was done in IRAF.

ISIS

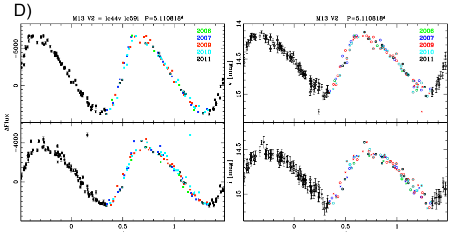
A reference image (Figure B) was created by combining the best six *V* and *I* images. The combined images (IRAF result) were subtracted using ISIS from the reference image and then averaged to produce the variable images in *V* (see Figure A) and *I* separately. This displays those stars that have had variability over the timeframe of observation, eliminating the majority of stars not observably variable. The subtraction process makes it possible to find variable stars in the crowded cluster center, but the process requires the outer edges of the images be trimmed off, eliminating distant variables.

C)



C) (Left) An example of a flux-time plot produced for a variable star using ISIS. This diagram shows the well-studied Cepheid Variable star V2. Blue and red points are *V* and *I* fluxes, respectively. The sporadic change in flux is due to this star having a short pulsation period relative to the sampling timescale. (Right) Another plot of V2 showing the instrumental magnitude from DAOPHOT.

D)



D) (Left) Using the well-known pulsation period of V2, a flux-phase diagram can be created using the ISIS output. (Right) This magnitude-phase plot for V2 results from DAOPHOT output. Both phased light curves are excellent, giving us confidence in the methods and data.

DAOPHOT

After IRAF, another process to find variable stars was used with the software DAOPHOT. The same reference image made for ISIS was used in DAOPHOT. In this package, the magnitude is calculated for every individual star in every image. A significant change in the magnitude of a star flags it as variable. Overlapping stars near the crowded cluster center are difficult to measure reliably.

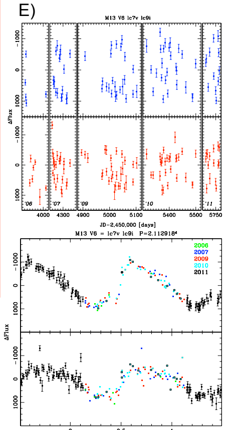
ISIS and DAOPHOT comparison

The flux *vs.* time and phase plots produced through the process in ISIS were compared to the magnitude *vs.* time and phase plots produced from DAOPHOT. One difference is that the star's brightness (*y*-axis) is in magnitudes for DAOPHOT, in contrast to flux values for ISIS (Figures H and I); magnitudes are often easier to interpret. For stars nearer the cluster center, DAOPHOT data tend to have more scatter than ISIS data. However, DAOPHOT can measure the outer variables that ISIS misses. Thus, there are advantages and disadvantages for both the Image subtraction (ISIS) method and measuring magnitudes using DAOPHOT. The innermost variables were studied using ISIS and are presented in a different poster.

SuperMongo

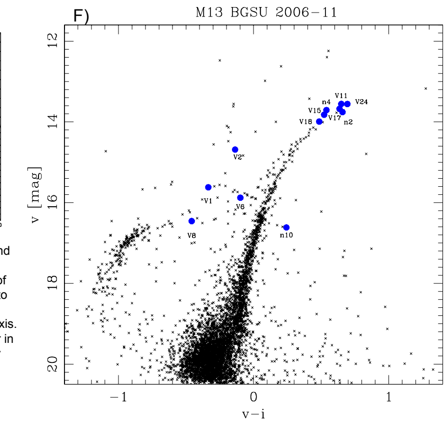
Finally, using the light curves produced from ISIS or DAOPHOT, a macro file for each variable star was made for the graphing program SuperMongo. These output the flux *vs.* time plots (e.g., Figure C-*l*) or the magnitude vs time plots (Figure C-*r*). For those variables with known periods, a flux or mag. *vs.* phase plot (Figure D) was also made, illustrating the star's change in brightness if its pulsation is consistent (regular) and not erratic.

E)



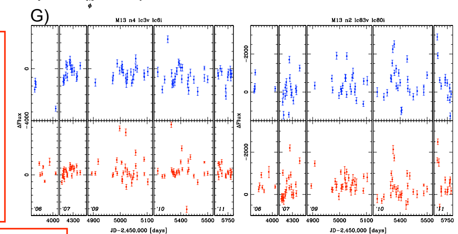
E) The two figures above are the flux and magnitude versus time plots for the Cepheid variable V6. The short period of 2.112918 days (used in the phase-plot to the right) is not apparent on these time plots because of the scale of the time axis. In *I*, the flux seems consistent, however in the magnitude there was an abnormally high magnitude value (inverted) around 5000 days. This is not an error by DAOPHOT, but rather a high sky background on that image.

F)



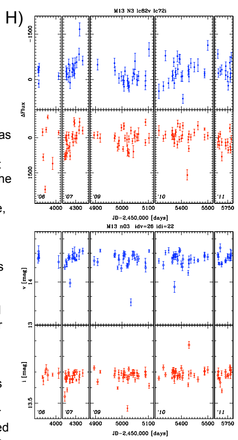
F) The color-magnitude (luminosity *vs.* surface temperature) diagram in magnitudes, produced from DAOPHOT. Each point represents one star in the cluster, and blue circles mark variable stars. Specifically, V2, V1, and V8 exist on the instability strip for this cluster (the portion of the diagram that variable stars should reside in). V6, however, seems to be outside of this strip, yet it is accepted as a Cepheid variable. The labels show three new variable stars, however the coordinates of N2 and N4 indicate they are V20 and V33, respectively, from Samus (2009).

G)



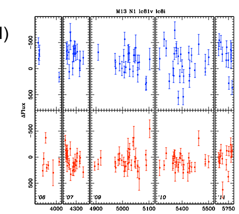
G) These are flux-time plots for V33 and V20 respectively. From these plots, it is apparent that the stars are variable. However, the period of the variability, if it is regular, is difficult to deduce from these figures. Thus, the phase plots were not created since the period could not be determined. The color-magnitude diagram (E) also plots these two stars among the other variable red giant stars, where other long period variables (V11, V15, V18) reside. Thus, these stars have variability, luminosity, and surface temperature values consistent with stellar evolution theory.

H)



H) This pair of figures are the magnitude and flux plots for the new variable labeled N3. Both of these plots show little variability. The magnitude diagram has some extremely low and extremely high values, but not consistent changes. The flux diagram, on the other hand, shows more change, however the scale for the flux is very small and so these changes are most likely not physical changes in the star's luminosity. In addition, no period for N3 could confidently be found using PDM. Thus, this star is at the threshold of our variable star detection.

I)



I) This figure shows the *V* and *I* flux plots for the new suspected variable N1. The degree of variability appears to be larger than the photometric uncertainty indicated by the error bars (e.g., *V* in 2010), but no coherent variation is apparent, suggesting N1 has a short period ($P < 20$ d). However, we could find no convincing period using PDM, and the variations do not appear well-correlated between *V* and *I* as expected. Thus, this star is also at the threshold of our variable star detection, and like N3, we list it as a suspected variable star. It appears that our observations have added no *new* variables to M13, though they have provided better long-term CCD-based photometry for the Cepheid and LPV stars in this cluster.

Conclusion

Comparison of the plots produced by DAOPHOT and ISIS shows advantages and disadvantages for both. The analysis here shows evidence that certain stars are not variable that were thought to be in previous studies. In addition, some new long period variable stars were discovered. However, the periods for these new stars could not be deduced due to two complications; either they were too short in period for the time interval here to determine, or not enough observation ("signal") was collected to show confidence in a period. We list these stars as suspected variables (N1, N3, etc). Finally, RA and DEC for each variable star on the edges of the cluster were determined.

References

- Alard, C., 2000, *Astron. and Astrophys.* , 144, 363
- Kopacki, G., Kolaczkowski, Z., & Pigulski, A., 2003, *Astron. and Astrophys., 398*(2), 541-55
- Samus et al. 2009, *Publ. Astron. Soc. Pacific*, 121, 1378
- 2MASS: Strutskie, M. F. et al. 2006, *Astron. Journ.* 131, 1163
- DSS image: http://archive.stsci.edu/cgi-bin/dss_form