Globular clusters: Stellar evolution and the astrophysical distance ladder

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Globular clusters (GCs) provided astronomers with several interesting mysteries for the first half of the twentieth century. Beginning with the discovery by Bailey (1895) that some of these clusters were extremely rich sources of periodic variable stars, and especially after the discovery of the Cepheid period-luminosity relation by Leavitt (1908), GC observations were mined both for the purposes of understanding the mechanisms of variability, and of use in determining distances and the distance scale of the Universe. Both studies, involving dozens of notable astronomers, reached early productive peaks in the 1910s. First, it was shown that the periodic variability of these "cluster variables" is the result of fundamental-mode, radial acoustic oscillations (Shapley 1914). Subsequently, cluster variables were used, along with Leavitt's Law[1], to measure the 3D distribution of GCs. This work revealed that the Solar System lies a considerable distance from the center of this distribution, and that the center lies in the direction of the center of the Milky Way in Sagittarius (Shapley 1919). It also revealed that the distance to the center was unexpectedly large, enough so that some astronomers began to question the extragalactic nature of the spiral nebulae. Although Hubble (1925) soon provided proof that spiral nebulae are galaxies independent of the Milky Way, the distance-scale questions, crystallized in the write-ups from the Shapley–Curtis debate (1921), still resonate in astronomy.

Meanwhile, astronomers began to study the stellar populations of GCs, only to find an apparently separate mystery. Colors and magnitudes of nearby stars, and of nearby open clusters such as the Hyades, had been arranged in (Hertzsprung–Russell) diagrams, then called "color–magnitude arrays," in which the familiar main sequence, giant branch, and the "Hertzsprung gap" between them are prominent. HR diagrams of globular clusters looked nothing like this. From the first (M13; Shapley 1915), they showed one branch with magnitude increasing with color index — that is, the brighter stars are redder — which is nearly perpendicular to the main sequence, in which the brighter stars are bluer. They also revealed a second branch of stars with about the same magnitude, spread to bluer colors from the first branch. If the first branch were aligned with the giant branch of nearby stars and open clusters, the second would lie in the Hertzsprung gap, and the cluster's stars would be considerably less luminous than what would be implied by the GC's Leavitt-law-inferred distances. For the next three decades, all of these features remained unexplained; as late as mid-century, it was possible even for those with forty years of experience in the subject to be completely befuddled (g.g., Shapley 1949).

Shortly after 1950, these mysteries were all resolved together, in a single, classic, experiment. The main experimenter, Walter Baade, combined two recent advances to which he had privileged access: the brand-new 200-inch Hale telescope at Palomar Observatory (1948), then the largest telescope in the world; and especially the new generation of red-sensitive astronomical emulsions by Eastman Kodak (1950). Thereby, Baade took unprecedentedly-good images of a few GCs in B and V. Then, he turned graduate students Chip Arp and Allan Sandage, and postdoc Malcolm Savedoff, loose on the images. The key turned out to be observations of M3, with exposures up to one hour at B and V (Sandage 1953a, Sandage 1953b, PhD thesis). In these observations, the cluster's main sequence was detected, and all became clear: the origin of the GC HR diagrams in stellar evolution, and the

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[1]With the wrong luminosity scale and zero point. Shapley's assumption was a great insight, but classical Cepheids turn out to have a period-luminosity relation very different from cluster variables. This is one reason that Shapley's result for the Galaxy diameter was so far off.

identity of cluster variables with RR Lyrae.[2] Immediately, there was a basis for determining the ages of globular clusters. Immediately, by main-sequence fitting of M3 to calibrate its RR Lyraes, the distance scale of the Milky Way was resolved. Eventually,[3] this turned RR Lyrae stars into robust, accurate standard candles in the distance ladder.

In this project, you will repeat the classic experiment by Baade et al., with one additional, modern step:

- Take LRGB images of a globular cluster, with a limiting magnitude of 22–23 in the B, G, and R filters.

- Take RGB images of RR Lyrae with accurately measured parallax, interleaved with your cluster images. Late enough in the semester you can use RR Lyrae itself, or better yet NR Lyrae.

- Identify the cluster's variable stars and measure their light curves. Do the same for the extra RR Lyrae.

- Measure the magnitudes of the cluster stars down to the magnitude limit, and create a HR diagram in G vs. B-R.

Here are some globular clusters from which to choose:

Top ten variable-rich globular clusters in the Northern sky	Ten brightest northern globular clusters, summed over the entire cluster
NGC 5272 (M3)	NGC 5904 (M5)
NGC 5904 (M5)	NGC 6205 (M13)
NGC 7078 (M15)	NGC 5272 (M3)
NGC 7006	NGC 7078 (M15)
NGC 6934	NGC 6341 (M92)
NGC 5024 (M53)	NGC 5024 (M53)
NGC 2419	NGC 6838 (M71)
NGC 5466	NGC 6779 (M56)
NGC 6205 (M13)	NGC 6934
NGC 6341 (M92)	NGC 6760

Be sure to answer the following questions in your analysis:

- How many frames, and of what exposure time, are necessary to reach the magnitude limit in all of the filters? How many nights should be planned for the project?

- How is it that we can reach the same magnitude limit with the Mees 24-inch telescope that Baade did with the 200-inch?

- Do you reach the magnitude limit you expect? If not, why not?

- How many RR Lyr variables do you detect in your GC? What is their range of periods and amplitudes, and what is their average G magnitude? How do their periods compare with simple models of radial stellar oscillation, such as the one-zone model discussed in Carroll & Ostlie?

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[2]The periodic variability of RR Lyrae, as well as the strong resemblance of its light curve and period to the cluster variables, was discovered early in this story by Fleming (1901). Astronomers suspected the identity of cluster and RR Lyrae variables all along but could not prove it. As the number of known variables and the range of their periods increased, and as unknowns such as extinction and multiple different kinds of variability sowed confusion, astronomers became more modest in claiming their identity. Shapley (1949) in his review paper, and Sawyer (1939) in her catalog of cluster variables, do not refer to RR Lyraes at all. The Baade group started their first publications (Arp et al. 1953, Sandage 1953a) calling them cluster variables, only switching confidently to "RR Lyrae stars" partway through each paper.

[3]The parallax of the nearest RR Lyrae star — RR Lyrae itself — was first measured by the *Hipparcos* mission in 1992. According to *Gaia* data release 3 (2020), this parallax is 3.9849±0.0265 mas, for a distance of 250.947±1.6688 pc.

- How many variables do you detect that are not RR Lyr stars?

- What is the distance to your GC, and the uncertainty in this distance, inferred from your observations?

- In your GC's HR diagram, where are the main sequence, red giant, and asymptotic giant branches, horizontal branch, and blue stragglers?

- Plotting absolute G magnitudes on the vertical axis: how does your result compare to the HR diagrams of nearby stars?

- How does the standard model of stellar evolution account for the features in your GC's HR diagram, and for its differences with that of nearby stars?

- How old is your GC? (Consult the isochrones in the Dartmouth Stellar Evolution Database.)

- Calculate the mean and standard deviation of the absolute G magnitude of the cluster's horizontal branch stars, leaving out the variables as you do. Could you use this as a standard candle? If so, how? If not, why not?

Include with your report your best composite true-color image of your GC. Archive this image, and all of your raw and reduced data, on the Mees analysis workstation.

Additional reading

Astronomy 142: lectures 7, 11, 15, 19

Astronomy 241: lectures 15, 16, 17, 18

Vandenberg et al. 1996, ARA&A 34, 461–510.

Previous results: PHYS 243W paper on M15 by Ryan Rubenzahl '18 and Bo Peng '18