Stellar Photometry of the Globular Cluster M2

Rafael R. Custodio, California State University, Sacramento
Advisor: Dr. Eric Sandquist, San Diego State University

My research project was the photometric analysis of the globular cluster M2. I conducted standard IRAF image reduction using the DAOPHOT photometry package. The data was used to construct color-magnitude diagrams to identify stars in different stages of their evolution. The morphology of the horizontal branch (HB) was compared to synthetic data sets to predict the evolution of asymptotic giant branch (AGB) stars and the behavior of the $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ nuclear reaction. For models of $0.64M_\odot$ initial mass and metallicity of $Z = 0.0006$, a theoretical value for R_2 $[N_{AGB}/N_{HB}] = 0.130 \pm 0.001$ was obtained. In comparison, our observational data yielded an $R_2 = 0.127 \pm 0.003$.

Introduction

My research project involved the study of horizontal branch (HB) stars in the globular cluster M2. HB stars are stars that have left the red giant branch (RGB) and have initiated helium fusion in their cores. An HB star's location is determined by its heavy element content and the amount of mass lost during the RGB stage; stars with significant mass loss appear on the blue end of the HB (Blue HB) and, inversely, stars with minimal mass loss emerge on the red end (Red HB). HB stars have initiated helium fusion in their cores with a thin hydrogen fusion shell outside the core. The asymptotic giant branch (AGB) is the next stage of stellar evolution. AGB stars lack the mass needed to initiate carbon and oxygen fusion. The contracting core, in conjunction with the hydrogen-burning and helium-burning shells, increases the star's luminosity, but the larger radius decreases surface temperature.

Despite our fairly comprehensive knowledge of the 3α nuclear reaction $[{}^4He + {}^4He \rightarrow {}^8Be + {}^4He \rightarrow {}^{12}C + \gamma]$, which is a major energy source for HB stars, there is currently a lot of uncertainty around the other major helium fusion reaction $[{}^{12}C + \alpha \rightarrow {}^{16}O + \gamma]$. By being able to accurately predict the evolution of a star through the HB, we should, in theory, be able to predict evolution through the AGB as well. Since we are unable to create the conditions needed to properly study the $^{12}C(\alpha,\gamma)^{16}O$ reaction here on earth, we look to stars in order to better understand this reaction.

Cassisi et al. generated synthetic models of HB and AGB stars for various initial stellar mass and metallicity based on our current knowledge of stellar evolution. These models employ data representing the best current understanding of physics (including nuclear reactions). By modeling the morphologies of HB stars, we can test our understanding about the way these stars evolve.

Observation and Reduction

The images we used for observational analysis were taken on the 2.2m ESO telescope in La Silla, Chile in 2004. The ESO WFI (Wide Field Imager) is an array of eight (8) 2046×4096 pixel CCD chips with an average field of view of 8'×16' for each chip. There were a total of 13 images taken: four (4) in U band (3650Å), two (2) in B band (4400Å), four (4) in V band (5500Å), and three (3) in I band (8800Å). Due to time constraints, and the fact that the cluster was centered on one chip, only one chip was reduced and analyzed. After using standard IRAF image reduction, photometric analysis was conducted using DAOPHOT II and point-spread function (PSF) photometry in order to extract individual stellar magnitudes in each of the four filters. Information was compiled into a master data file that contained: star ID, x (position of star on x-axis in reference image), y (position on y-axis), m_U, σ_U, m_B, σ_B, m_V, σ_V, m_I, σ_I, χ^2. With the master raw file, color-magnitude diagrams (CMD) were then constructed (Fig.1)

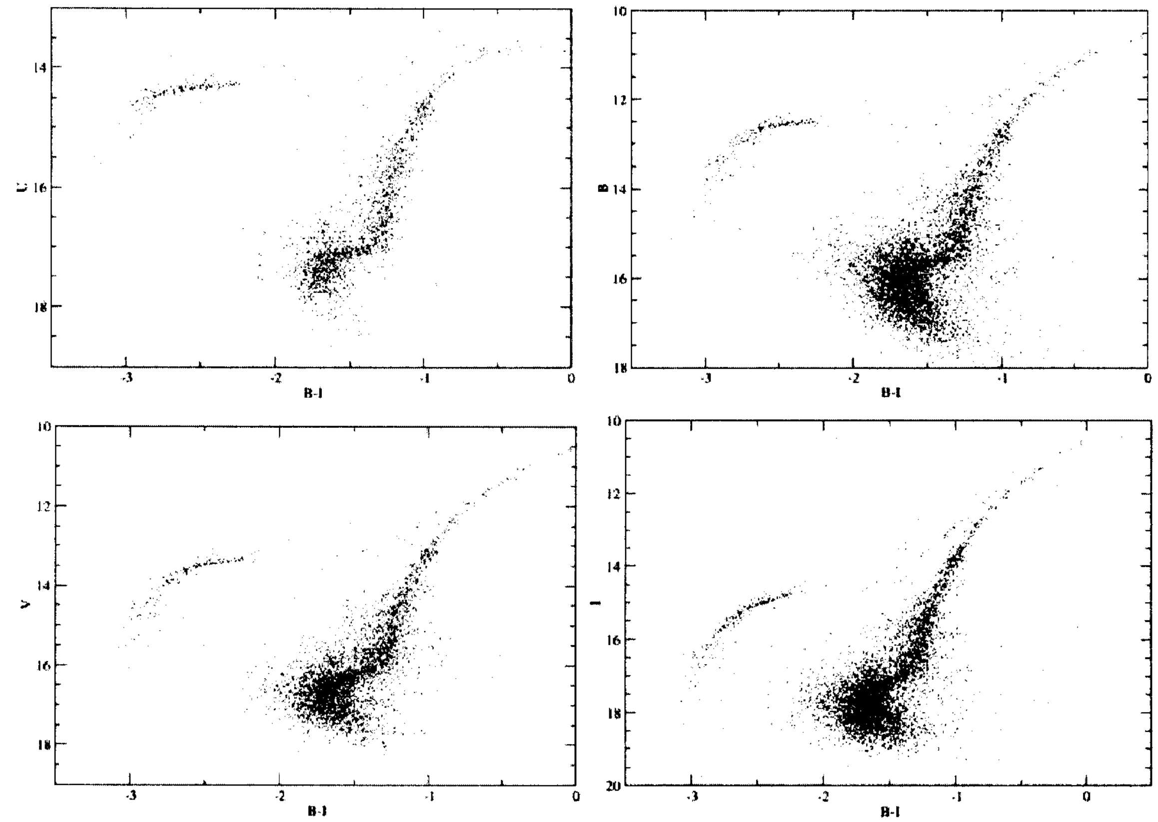

Fig. 1: Color-magnitude diagrams of M2

The initial CMDs that were drawn had severe scattering in the branches of the stars. I rectified this by eliminating the stars close to the center of the cluster from consideration. Accurate magnitudes for stars near the cluster center could not be determined due to light contamination for nearby stars in this dense region. Once corrected, the scattering was greatly reduced.

Analysis

The main goal of this project was to check the accuracy of the theoretical models by comparing the predicted value of R_2 to the observed value in order to learn more about the rate at which the reaction $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ is occurring. R_2 is defined simply as the ratio of the number of AGB stars to the number of HB stars. The R_2 value can give us an indication of the amount of time a star spends on the AGB relative to the HB. Following the simple relation:

Rate of fuel consumption × Amount of fuel = Fuel Lifetime

where the amount of helium fuel a HB star has is determined by the size of the convection zone mixing the core, and lifetime being related to our R_2 values, we can then learn how fast nuclear reactions are occurring in the core given the temperatures and pressures present there.

The way we are able to determine time spent based on number of stars can be explained by what I like to call the "Senior-Junior relationship". Since adulthood is a very long period of an individual's life compared to childhood, if you took a random sampling of the human population, you are bound to find more adults than children. This is due to the fact that people spend more time in adulthood than childhood. The same goes for stars. If there are more HB stars than AGB stars in a random sampling (like a globular cluster), then you can hypothesize that a star spends more time on the HB than the AGB. Following that logic, you can also say that the rate at which it consumes fuel (nuclear reaction rate) is faster on the AGB than HB for similar amounts of fuel. If we can accurately measure R_2 and use models to determine the amount of fuel used then we can gain a better understanding of the $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ nuclear reaction. My job was to verify the accuracy of the models by comparing the R_2 values.

Using the CMDs to locate and identify HB stars (Fig. 2.), we then looked at the predicted morphologies of the models (Fig. 3.). After correcting for distance and reddening, a best-fit model was selected. The observational data was then compared to the corrected model data (Fig. 4.). In order to insure accuracy, a histogram was generated to compare peak magnitudes (Fig. 5).

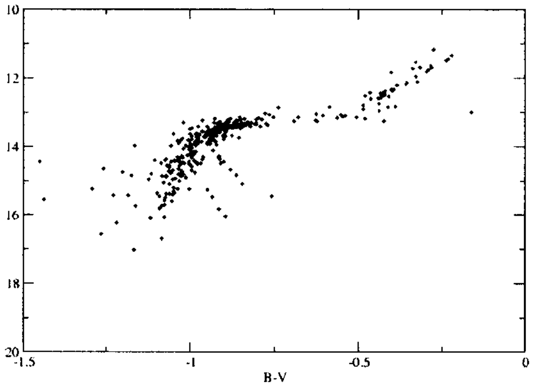

Fig. 2.:CMD of HB (dark) and AGB (light) in M2

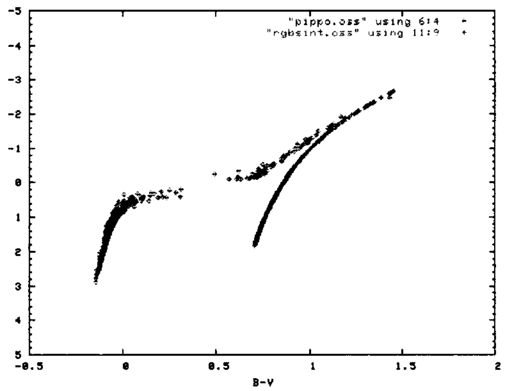

Fig. 3: Model of post-main sequence stars

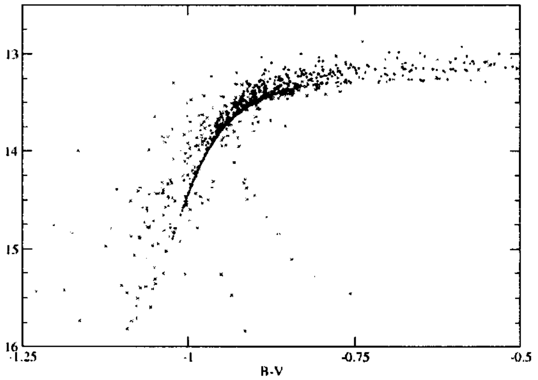

Fig. 4: Comparison of model (dark) HB and observed (light) HB

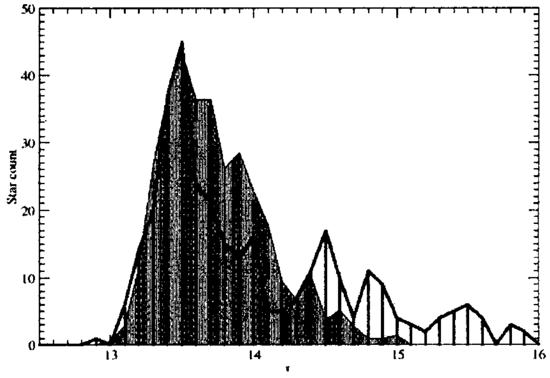

Fig. 5: Histogram of star counts vs I for model (shaded) and observed (bold lined) HB stars

A feature of the HB that was identified was the Grundahl "jump" (Grundahl et al. 1999) (Fig. 6). It is a break in the seemingly continuous HB. Grundahl interpreted the "jump" as due to radiative levitation and diffusion effects leading to hot (>11500K) HB stars having metal-enhanced and helium-depleted atmospheres. It has been observed that the "jump" coincides with a sharp decrease in surface rotation with hot HB having little or no rotation while cooler (<11500K) HB stars have large rotational velocities. Little is known about this "jump" and it should be studied further.

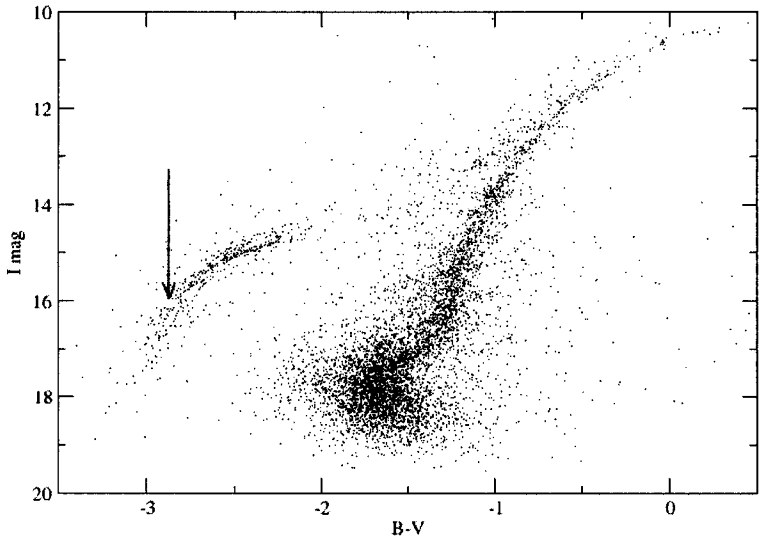

Fig. 6: CMD of M2 with Grundahl "jump" indicated by arrow

Conclusions

Based on the data from the models, the theoretical value of R_2 was calculated to be 0.130 ± 0.001. This translates to roughly 7.7 times as many HB stars to AGB stars. After compiling the photometry, with 331 HB stars and 42 AGB stars identified, an observational R_2 value was calculated to be 0.127 ± 0.003. This conclusion puts the number of HB stars at close to 7.9 times more than AGB stars. The observational value is 1σ from the theoretical value, confirming that for $M_0 = 0.64M_\odot$ and Z [Fe/H] = 0.0006, the theoretical models agree, within an acceptable degree of uncertainty, with the observational data. This moves us one step closer to fully understanding the $^{12}C + \alpha \rightarrow {}^{16}O + \gamma$ process, since we can accurately predict the rate at which this reaction occurs within stellar cores for a given amount of fuel and at a given temperature and pressure.

Acknowledgements

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References:

Cassisi, S. et al. 2004, A&A, 426, 641
Grundahl, F. et al. 1999, ApJ, 524, 242
Catelan, M. 2005, astro-ph/0507464
Peterson, R. C., Tarbell, T. D. & Carney B. W. 1983, ApJ, 265, 972