# Stellar Photometry of the Globular Cluster M15

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Photometric analysis of CCD images of the globular cluster Messier 15 in B, V, and I bands yields a ratio of asymptotic giant branch stars to horizontal branch stars of 0.186. Comparisons between the observed ratio and theoretical models indicate that the observations are almost $2.5\sigma$ above the predicted value. This implies that stars spend a higher percentage of time on the asymptotic giant branch relative to the horizontal branch than the models indicate.

## Introduction

The focus of my research was to test our understanding of how long low-mass stars spend in the late stages of their lives, namely the asymptotic giant branch (AGB) and horizontal branch (HB). HB stars have helium fusion occurring in their core with a shell of hydrogen fusion outside the core. AGB stars have finished fusing helium in their core, and instead have a carbon and oxygen core with a shell of He fusion. Since evolved stars in a globular cluster start out with approximately the same mass and metallicity, the number of stars in any given stage of evolution is proportional to the time they spend there. How long a star spends on the HB depends on how long it takes to burn through the He in its core. Two factors primarily affect how long it takes a star to burn its helium, the rate of the fusion reaction and the size of the convection zone that brings more He into the core. The conditions under which the fusion reactions occur are not practical to reproduce on Earth, so we must test our theories against computer models. Given models of stars with the same mass and metallicity as those in an actual globular cluster, the ratio of AGB stars to HB stars can be used as a test. This ratio of AGB stars to HB stars is called the $R_2$ ratio. If the model and observational data agree, it would suggest they are a good representation of the processes controlling He fusion in stars. If the data does not agree it would suggest an error in the model either with the rate of the fusion reactions or the size of the convection zones.

## Observations and Reduction

The images used in my research were taken on the Canada-France-Hawaii 3.5 m telescope using the CFH12k camera. The camera is an array of twelve CCD chips, four of which contained the majority of the globular cluster's core. The field of view for each chip is approximately 7' by 14'. My research had to be completed in a limited amount of time, so I focused on a single chip with the largest amount of stars and fewest chip imperfections. Observations were taken in three separate filters: B (4400 Å), V (5500 Å), and I (8800 Å). Each filter had nine images, six of which had the same exposure time and three more in a series of 1, 20, and 60 second exposure times.

The photometric analysis of the images was done using DAOPHOT II and various point-spread function photometry programs to find the instrumental magnitudes of each star in the image. After this was done for each image, the stars from different filters were matched and combined to form a master list with instrumental magnitude in each filter. The master list of star magnitudes was used to create various color-magnitude diagrams. After looking at many combinations, I vs. B-I was used in the final analysis because of the clear separation of the branches I wanted to focus on.

## Analysis

The first step in obtaining the $R_2$ ratio is identifying HB stars and AGB stars on a color-magnitude diagram (CMD). Figure 1 shows the CMD I used to isolate the AGB and HB stars. The stars were selected using a Fortran program that identifies all of the stars inside a polygon defined by coordinates on the CMD. The figure below to the right is the CMD with the horizontal branch stars signified by squares and the asymptotic giant branch stars represented by triangles.

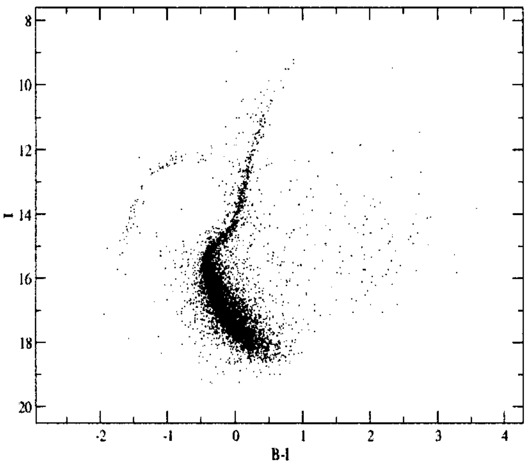

Fig. 1: I vs. B-I CMD

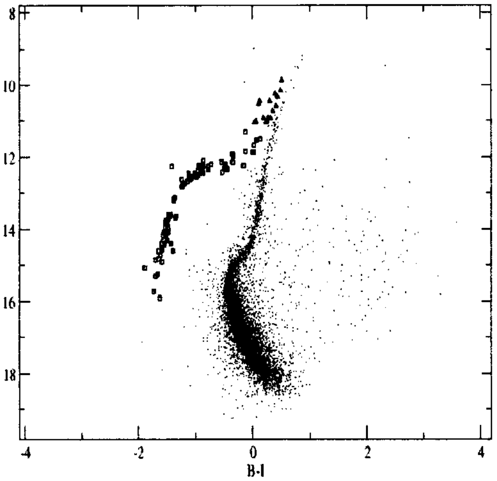

Fig. 2: I versus B-I CMD with HB and AGB

The separation between the horizontal branch and asymptotic giant branch was made based on a characteristic grouping of stars that signifies the beginning of the AGB. The observed ratio was $R_2 = N_{AGB}/N_{HB} = 16/86 = 0.186 \pm 0.034$. The error for that ratio was determined using Poisson statistics. The next step was to find the globular cluster model with similar initial conditions to those that exist in M15. I matched several features of the color-magnitude diagrams of the models and the actual cluster. While no model was a perfect match due to the bimodal nature of the horizontal branch in my cluster, the best fit was a mass of 0.68 solar masses and a heavy element mass fraction Z=0.0003. The CMD corresponding to this model is displayed below. The bimodal nature of M15's horizontal branch occurs because stars lose different amounts of mass on the transition from the red giant branch to the HB. Stars that lose a larger amount of mass end up on the blue end of the branch, these stars have smaller convection zones than stars on the red end of the horizontal branch. Stars that are not stripped of much mass end up on the red HB near the AGB. M15 has a larger concentration of stars on the blue HB, so the model I chose as the most accurate representation of M15 also had the largest concentration of its HB stars in that region. Once the model was chosen, the number of HB and AGB stars was given. There were 72 AGB stars and 722 HB stars in the model, yielding an $R_2$ of 0.108. The difference between the theoretical and observed $R_2$ values is 0.078 or $2.3\sigma$.

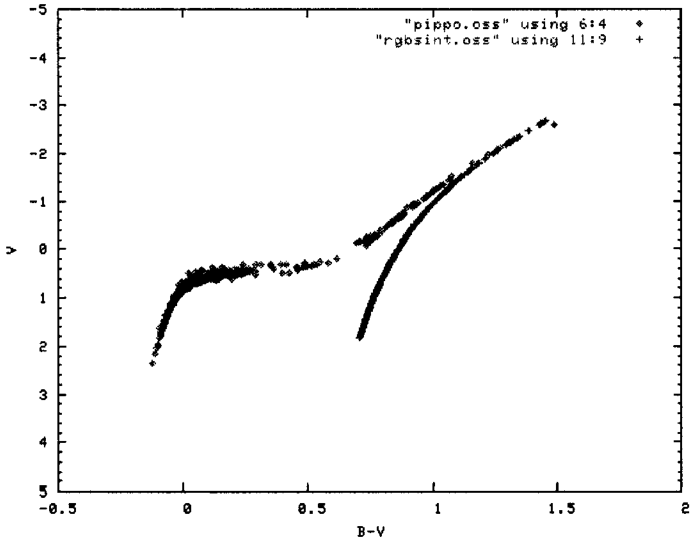

Fig. 3: Theoretical CMD

## Conclusions

A comparison between the theoretical $R_2$ value and the observed $R_2$ value suggests there is a flaw in the way stellar evolution in the horizontal branch and asymptotic giant branch is modeled. The observed $R_2$ value was 0.186 and the theoretical value obtained from the model was 0.108. The observed value being 0.078 higher indicates that the stars spend a lower percentage of their time on the horizontal higher indicates that the stars spend a lower percentage of their time on the horizontal branch than the theoretical models say they should. This means the stars burn through the helium in their core at a faster pace. The disparity could be accounted for in at least one of two places: the fusion reactions run at a faster pace than currently believed or the convection zones bring less helium to burn into the core.

Two major processes occur in the core when it is fusing helium. One, the 3α reaction, is fairly well understood and consists of $^4He + ^4He \rightarrow ^8Be + ^4He \rightarrow ^{12}C + \gamma$. The reaction that is not very well understood is $^{12}C(\alpha,\gamma)^{16}O$ reaction ($^{12}C + \alpha \rightarrow ^{16}O + \gamma$). For the models created by Cassisi et al. to match the observed data, the $^{12}C(\alpha,\gamma)^{16}O$ reaction would have to occur at a faster rate. This would mean stars burn through their core supply of helium faster and would move on from the horizontal branch to the asymptotic giant branch faster. Another aspect that could affect how long stars in a globular cluster stay on the horizontal branch is the extent of the convection zone transporting helium into the core. The more helium the convection zone brings to the core, the more helium the star must process before moving on to the asymptotic giant branch. A star with a larger convection zone would have more helium transported to the core, while a star with a small convection zone would have less extra helium to burn and transition to the AGB sooner.

The results of my research yield a limited amount of information. While the results suggest stars are moving through the Horizontal Branch faster than theoretical models, they give no indication which cause is responsible for the errors in the model. The theoretical models could have convection zones that are too large or they could have the $^{12}C(\alpha,\gamma)^{16}O$ reaction occurring at too slow of a pace. It could also be a combination of the two circumstances that made the model's $R_2$ ratio so much lower than the observed value. Additional work with globular clusters having different chemical compositions can help identify the source of the discrepancy.

## Acknowledgements

My advisor, Dr. Eric Sandquist, for always being there to answer my many questions; Rob Custodio for his help in solving numerous problems; all of my fellow REU colleagues; the SDSU Astronomy faculty for their valuable lessons; and the National Science Foundation for providing funding.

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