Distance to NGC 2639 via TRGB

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1 Introduction

Red Giant Branch (RGB) stars are low-to-intermediate mass giant stars that follow the main sequence before helium ignition. These stars have an inert helium core surrounded by a shell of hydrogen fusing via the CNO cycle. Compared to main-sequence stars of the same temperature, RGB stars are much larger and more luminous, with K and M classes being common. For stars with mass $< 2M_\odot$, the central temperature and density become high enough for the triple-alpha process to begin, resulting in the Red Giant Tip (TRGB). However, stars with mass $> 2.25M_\odot$ burn helium without their core becoming degenerate and do not exhibit helium flash. In very low-mass stars (mass $< 0.5M_\odot$), the core is never hot enough to ignite helium. When helium burning is initiated, it results in an abrupt decrease in luminosity and a shift toward bluer colours, creating a discontinuity in the color-magnitude diagram that is apparent in optical and near-infrared wavelengths. The luminosity generated by the helium-burning core becomes comparable to that of an entire galaxy but only lasts for a few seconds. The TRGB feature arises at the onset of core helium burning in low-mass stars, and it occurs at a predictable luminosity that can be calibrated and used as a standard candle. The TRGB luminosity is typically measured in the r or i-bands, where the luminosity has little dependency on stellar age or stellar metallicity. This makes them a standard candle with an SDSS i-band absolute magnitude of -3.44 ± 0.1 (Bellazzini, 2008).

2 Aim

Our goal is to determine the age of the NGC 6791 cluster of stars using the TRGB distance method. This cluster is known to be one of the oldest open clusters, and it contains stars with SDSS g, r, i band magnitudes ranging from 9 to 24. To achieve this, we will plot the observed stars on a Hertzsprung-Rusell (HR) diagram, and then use the TRGB feature to estimate the cluster's luminosity. Previous studies have suggested that NGC 6791 is located between 4086 and 6918 parsecs away from us (See SIMBAD), and we will use this range to validate our findings. Through this process, we hope to gain a better understanding of the formation and evolution of this ancient open cluster of stars.

3 Target and Observations

On the night of March 23rd, 2023, we used the GROWTH-India telescope to observe the NGC 6791 cluster of stars (as in Vishwajeet did all the observations). The telescope has an aperture of 70 cm and a field of view of 0.7×0.7 degrees, with a pixel scale of 0.7 arcseconds per pixel. We took a total of 12 images, with 4 images each for the i-band, g-band, and r-band filters. The exposure times for each band were 10s, 40s, 120s, and 240s. The telescope is located at Hanle, Ladakh, which is 4500 metres above sea level at 32°46'44.1"N 78°57'55.1"E.

4 Data Analysis

4.1 Photometry

The following photometry steps were performed based on the GROWTH Astronomy School 2020 to obtain the magnitudes of the sources in the entire field for all the 12 images:

- Using Vizier, the SDSS catalog was queried in a 50-arcmin diameter around the source coordinates and downloaded to obtain all the known sources in the field and their corresponding

SDSS g,r,i magnitudes. These are required for the zero-point calibration that will be performed later on.

- The raw image was passed along to the Source Extractor software with the following configuration key parameters:
  - DETECT_THRESH = 2, ANALYSIS_THRESH = 2: Number of standard deviations above the background noise for a pixel to be considered a source
  - DETECT_MINAREA = 5: Minimum number of neighboring pixels for something to be called a source
  - PHOT_APERTURES = 10.0: Diameter for the aperture around a detected source for getting counts and performing photometry. The number was chosen from the FWHM (max) of a sample of sources in the field using DS9. This number was also reasonably close to the flattening of the curve of growth obtained for the aperture diameters ranging from 4-14 pixels.
- Common sources from both the detected set from Source Extractor and the SDSS catalog were obtained. The instrumental magnitude is just $-2.5\log(\text{background-subtracted-flux})$. This value was compared to the relevant magnitude for the same source in SDSS catalog to obtain zero-point offsets. The mean of this was taken.
- The following three methods of obtaining source magnitudes were compared:
  - Annulus method: No. of counts in the 10-pixel diameter aperture was obtained. No. of counts in an annulus of diameter 20 pixels and width 10 pixels was obtained. This value was normalized and multiplied by the aperture area. Source magnitude was obtained by adding zero-point correction to -2.5log(background-subtracted-counts).
  - Photutils background subtraction: Using the photutils Background2D package, a background image for the entire field was obtained. Background subtracted flux/counts were directly obtained by subtracting the raw image counts and background image counts in the 10-pixel diameter aperture. Source magnitude was again obtained in a similar way.
  - Sextractor magnitudes: The zero-point correction was added to the background-subtracted source magnitudes directly output from Source Extractor to get the source magnitudes

  For all further analyses, Source Extractor magnitudes and corresponding errors were used for reasons explained in the Discussion section.

4.2 Combining exposures and HR diagram

The following analyses steps were employed to obtain the HR diagram from the obtained magnitudes across all exposures and across all bands:

- For each band, magnitude vs magnitude error was plotted (See Figure 1). For the first two photometry methods, error was obtained through

$$\sigma_{flux}^2 = N_{sky} + N_{background})$$

  . Magnitude error was obtained through the formula

$$\Delta m = \frac{2.5}{\ln(10)} \frac{\sigma_{flux}}{flux}$$

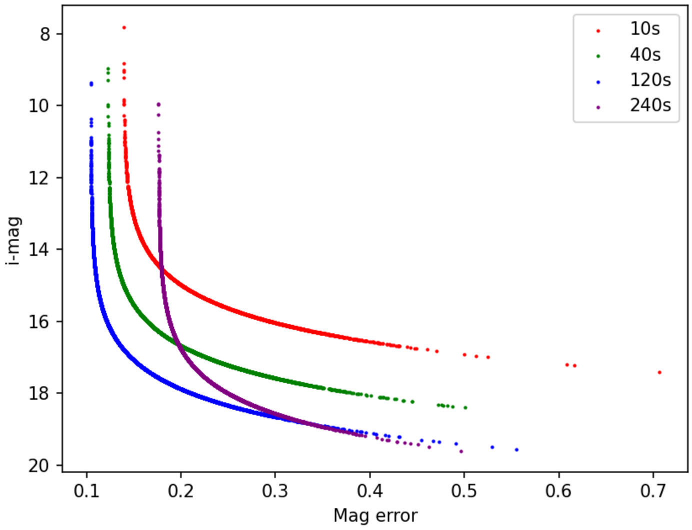

Figure 1: Representative Magnitude vs. Magnitude error plot for the i-band 10s, 40s, 120s, and 240s. Other bands follow similar trends.

and adding the zero point error to this. For the magnitudes directly obtained from Source Extraxtor, the MAG_ERROR_APER was directly read off and zero point error added.

- Stars in each exposure image were cross-matched to stars in every other exposure image. For these common stars, the magnitude value of the higher exposure image was chosen, as the magnitude error for the higher exposure images is lower (see Figure 1).
- Similar cross-matching of sources was done across all three bands. Only sources that were detected in all three bands and whose respective magnitude value was determined were chosen.
- With this, the HR diagram was plotted for i-band magnitude vs. g-i color and r-i color for different cluster diameters (sources only within a given number of arcmin from the cluster center were chosen) until a decent HR diagram was obtained. This radius was found to be 6'. In fact Kaluzny and Udalski (1992) used a diameter of 8' to plot their HR diagram and found the radius at which star density falls to half to be 142". Figure 2 shows the two HR diagrams. The star picked as the tip is mentioned in the captions.
- Roughly 2000 sources were detected in the 6' radius circle. The number of field stars not belonging to the cluster was estimated by counting the number of sources in a different 6' radius circle far away from the cluster. This number was found to to be roughly 600. These background stars not belonging to the cluster but lying within the 6' radius circle from the cluster center could be contributing to the noise in the HR diagrams.

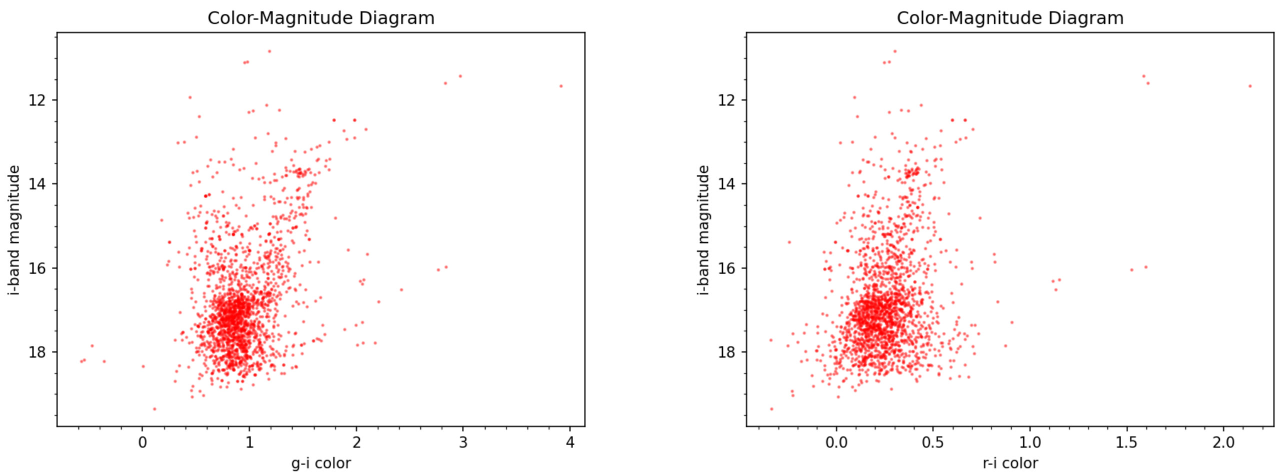

Figure 2: (Left) i-band magnitude vs g-i color for sources within a 6' radius from the cluster center. The tip is chosen as the source with the lowest magnitude around a g-i color of 3. (Right) i-band magnitude vs r-i color for sources within a 6' radius from the cluster center. The tip is chosen as the source with the lowest magnitude around a g-i color of 1.7.

4.3 TRGB and distance to the open cluster

The apparent magnitude of the TRGB is thus obtained to be 11.42 ± 0.15. Given the absolute i-band magnitude of TRGB to be -3.44 ± 0.1, the distance to the cluster is obtained through the formula

$$d(pc) = 10^{((m_{app} - m_{abs})/5+1)}$$

as 9393 ± 2092 pc.

5 Results and Discussion

The lower bound of the distance obtained agrees with the upper bound of literature distances of 4086 to 6918 pc. The possibilities for the ~ 2000 pc discrepancy could be because a fixed aperture of 10-pixel diameter was used for all sources across all exposures. The counts in the brighter sources which appear across more pixels may be effectively counted but it could be that for the dimmer sources, neighboring stars are leaking into the aperture confounding the photon counts obtained for the source. The TRGB is amongst the brightest stars in the i band and is comparatively much dimmer in the g and r-bands (more so in the g-band). Due to the factor mentioned above, it could be that a neighboring star is leaking into the photometry of this dim g-band star giving an error in g-band magnitude, and hence the g-i color. It must be noted that an error of 0.5 magnitudes has the potential to cause a distance error of $\sim$2000 pc. So the reason mentioned above put together with zero point error and TRGB absolute magnitude calibration error could be the cause of the observed discrepancy. Performing PSF photometry, which involves fitting a point-spread-function (PSF) and obtaining counts for different sizes of spreads in point sources, is a more accurate method of obtaining source magnitudes and overcoming the limitations of aperture photometry.

Coming to the three different methods for performing photometry, using Source Extractor background subtracted magnitudes and the magnitudes obtained by performing background subtraction using the photutils background image, gave significantly better results in terms of the HR diagram compared to the magnitude values obtained using the annulus method. This could be because neighboring sources are entering into the annulus and throwing off the number of counts obtained for the background. Amongst the Source Extractor magnitudes and the photutils method magnitudes, there was no appreciable difference and the Source Extractor magnitudes and corresponding errors were used for all further analysis.

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