Krittika Summer Project 3.0

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Estimating Age of Clusters

Project Report

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Abstract

In this project, the age of a globular star cluster is estimated using photometry. Stars in a globular cluster are chemically homegenous, are of the same age and are at a similar distance from us. We can utilise these properties and plot the HR diagram of the apparent magnitude of the stars in different filters to estimate the age. Apparent magnitude in a given filter is obtained by performing Aperture and PSF photometry on the image cutouts of the cluster in that filter. Then, isochrone-fitting is performed on the HR diagram and the age of the cluster is estimated. The globular cluster M13 or NGC6205 is chosen for this project. The image cutouts for this cluster is obtained from the PanStarrs 1 data archive. Photometry is done using Sextractor and Psfextractor in Python. Theoretical isochrone models are obtained from MIST web portal.

Contents

Introduction

There are numerous methods to estimate the age of globular clusters. [1] list them as vertical and horizontal methods. Vertical methods are characterized by anchoring the Colour Magnitude Diagram to a standard reference point. This includes the Δv method,where the horizontal branch would be the reference point. There is also the white dwarf cooling sequence method where the white dwarfs are used to calculate the distance and hence the age. Under vertical methods there is also the conventional method of main sequence fitting. Isochrone fitting which is considered as a combination of the two methods. It is based on the fact that the position of main sequence turn off (MSTO) point is dependent on the age of the cluster. [2] suggests a new technique to estimate the age of the universe. For example, in the near infrared region around stars of mass $0.5 \odot M$ there appears a kink and magnitude difference between the main sequence turn off and this kink is highly dependent on age. Hence, recording this kink would lead to more accurate results. This project implements isochrone-fitting using the MIST models.

Theory

Evolution of Stars

Evolution of stars is a cyclic process where they are born out of dust and clouds and reach the end of their cycle to form dust again by stellar winds, ejection of planetary nebulae and supernova explosion. Interstellar medium is the source of all stars. Clouds fulfilling the Jean's criterion collapse under gravity and begin the formation of stars. The gravitaional collapse causes a freefall of mass and increase of density in parts of clouds. This process is complex and involves multiple collapse and shock waves. Shock waves occur because of the collision of the free fall mass with the collapsed core. This continues till hydrostatic equillibrium is established and gravitaional potential energy serves as the source of energy for these objects. They are mostly made of hydrogen gas and are called the protostar. The protostars continue to become T-tauri stars of rapidly varying luminosity and follow the Hayashi tracks. These tracks indicate almost a vertical line on the HR diagram, since the luminosity of the star decreases while temperature increases slightly. The increasing temperature due to the release of gravitational potential energy leads to a convective envelope limiting the protostar collapse and it decreases luminosity of the protostar.

Main sequence is the locus of stars where they start burning hydrogen to helium. They exit this sequence once hydrogen gets depleted. Depending on the mass of the protostars, they can enter the main sequence in various tracks however stars with mass below $0.072M_{\odot}$ would not enter the main sequence at all as they cannot achieve the core temperature required for hydrogen burning nuclear reactions. Massive stars with $M > 1.2M_{\odot}$ burn hydrogen to helium by the CNO(Carbon Nitrogen Oxygen) cycle which is highly temperture dependent hence leads to further rapid rise in temperature and burns faster. Stars of mass comparable with the Sun go through both CNO and PP(proton-proton chain) cycles and low mass stars can perform only PP chain. This difference in type of nuclear reaction is due to the suitable temperature conditions existing in those stars. In the main sequence these nuclear reactions are the major sources of energy of the stars unlike the pre-main sequence phase where gravitational potential energy was solely responsible for the star's luminosity.

When the hydrogen in the core gets depleted and a helium isothermal core begins to contract, the hydrogen burning shell begins to burn using the energy from the helium core and it is brighter than the previous hydrogen burning core leading the envelop around to expand, luminosity to increase and temperature to decrease. This is the scenario of a star of mass around $1M_{\odot}$. For stars of $5M_{\odot}$, or intermediate mass the core is convective hence, the entire star contracts releasing gravitational potential energy which increases the temperature slightly and increases the luminosity. Following this, the hydrogen shell starts to burn, temperature decreases, luminosity increases with expansion of the envelope and the helium core contracts. This is called the subgiant branch. As the core of these low mass and intermediate mass stars proceed to contract, it forms a deep convective envelope at the surface and expands into the core. This causes the products of the nuclear fusion and energy of the core to transport to the surface with further increase in luminosity. This outwards transport is called the first dredge up and this phase is called the red giant branch. The continued contraction of the helium core and the resultant temperature suffices the burning of helium or the alpha triple process, also highly temperature dependent. In low mass stars of less than $1.2M_{\odot}$, the contraction causes electron degeneracy in the core which promotes a sharp explosion called helium flash which lasts for a very short duration as the layers on the core absorb this sudden burst of energy. This high energy flash breaks the electron degeneracy in those stars and the core begins to expand again due to the burning of helium and pushes the hydrogen shell outwards causing it to cool down. In massive stars helium flash is absent because the core does not undergo electron degeneracy. The luminosity of the stars during helium burning decreases since hydrogen shell was the major source of this luminosity. These stars then enter the horizontal giant branch phase analogous to the main sequence line where the core expands, envelop contracts and temperature rises and moves to the right on the HR diagram. Once the helium core is depleted it follows a similar route as before with the depletion of hydrogen core only for shorter duration and at cooler temperatures. This phase analogous to Red Giant Phase during helium shell burning with a core having abundant Carbon and Oxygen is the Asymptotic Red Giant Branch. These low and intermdiate mass stars are not capable of burning the Carbon and Oxygen rich core and hence form planetary nebula followed by white dwarfs. Stars of very high mass ($> 40 \odot M$) tend to strip of their envelops during the red giant phase and collapse to neutron and black holes. During the collapse there may be release of gravitational potential energy leading to supernova.[3]

Classification of Stars

There are currently two kinds of classification of stars in use to completely describe the star -

- **Harvard Spectral Classification**
  This classification is based on the surface temperature of star and the presence and strength of Balmer lines. There are mainly 7 spectral types - OBAFGKM where O type star is the hottest ($30,000K$) and M type the coolest($3000K$).

- **Morgan Keenan**
  Two stars having the same surface temperature can have different luminosity if they are of different sizes evident from the Stefan-Boltzmann Equation-

  $$L = \sigma A T^4$$

  where σ is the Stefan-Boltzmann's constant, A is the surface are of the star and T is the temperature of the star. Hence there is a need for classification based on luminosity too. These are ($Ia - O$) extremely luminous supergiants, (Ia) luminous supergiants, (Ib) less luminous supergiants, (II) bright giants, (III) normal giants, (IV) subgiants, (V) main sequence dwarf stars, (VI or sd) subdwarfs, (D) white dwarfs.

[3]

HR Diagram

HR diagram or the Hertzsprung–Russell (H–R) diagram is a plot of the colour-magnitude vs. colour index(Colour-Magnitude Diagram - CMD) or a more theoretical version would be luminosity vs. the temperature of a star. Figure 1 is a typical HR diagram illustrating different types of stars at different stages in their lifetime[4]
The temperature axis is inverted. The main sequence runs from the top left to the right of the plot with the hottest and most luminous stars occupying the top left corner whereas the stars having less luminosity and temperature occupy the right corner. The subgiant, redgiant, horizontal branch are above the main sequence on the right becaue they are more luminous but less hot. The white dwarfs, have decreased luminosity but have high temperature , so they are found on the lower right corner. The main sequence turn off point is the point where the stars leave the main sequence. Since the hotter stars deplete hydrogen faster, they are the first ones to leave and hence the turn off point moves from top left to bottom right. Hence, lower the turn off point the older the cluster will be. HR diagram has proven to be very useful in plotting evolutionary tracks of different luminous objects in the sky. Isochrones is one such track which is the locus of all stars of the same age. Isochrones are produced using several numerical calculations using the initial mass function of the stellar population.

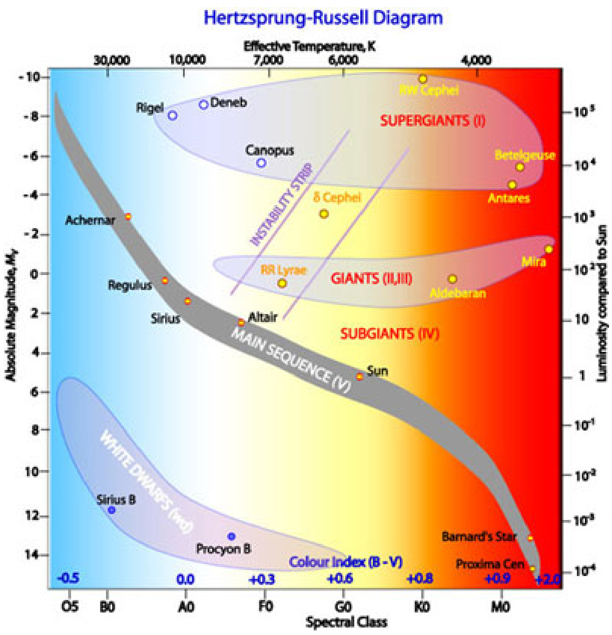

Figure 1: HR Diagram

Globular Clusters

Stellar clusters are formed from the same ISM (Interstellar Medium) and hence have very similar chemical properties and differ in parameters affected mostly by their initial mass. Globular clusters are densely populated clusters due to their high gravitational force. Low metallicity and stars of $1M_{\odot}$ at the main sequence turn off point indicate that they are very old stellar population.[5].Hence they have older and redder stars. They have longer lifespan because of their relatively greater stability due to their bounded structure as compared to the open clusters. This makes them perfect candidates to study to know more about the early stages of the universe because the age of the universe is around $13.772 Gyr$ whereas the oldest globular clusters are around $13.5 Gyr$ old[6]. Therefore it is belived that globular clusters must have clues about the formation of the universe.

Photometry

The technique of measurement of flux from a star is called Photometry. Aperture and Point Spread Function Photometry are the two kinds implemented in this project using Sextractor[7] and psfex[8]. Aperture Photometry involves background estimation, source detection, centroiding, and summation of flux.[9]

- Background estimation : There is non-zero flux from the sky which is included in the flux we recieve from the source. Hence we need a count of the background flux and correct the source flux for it. We do this by calculating the average flux in an annulus centered on the star such that it is made sure that the annulus is mostly free of light from any source.
- Centroiding : The center of the source is located and by setting the appropriate aperture size accurate values for apparent magnitude are obtained.

- Summation of flux : In the given aperture, all the photons are counted and summed. Aperture size must be the same for both faint and bright sources.

Point Spread Photometry is performed on stars which are crowded where obtaining an aperture around a single source is difficult. After performing a preliminary aperture photometry, a a point spread function created for the given frame is cross-correlated with the pixels of the source coordinates and it will result in the profile for all the stars in the image. Repeated fitting of the profile over the sources will result in better detection of sources and their magnitude.[10]

Methods and Procedure

The whole project can be divided into following steps-

1. Performing Aperture photometry
   Sextractor was used to perform Aperture photometry which produced a catalog of stars. The stars with non-zero flags were removed.

2. Performing PSF photometry on the resultant catalog to get a better luminosity profile for all the stars detected.

3. Performing Aperture photometry again
   Sextractor is again used, only this time the psf profile was given as input.The final catalog is produced.

4. Calibrating the obtained magnitudes
   PANS STARRS has a standard zero point of 25. This is added to all the magnitudes and the CMDs are plotted for all the filters

5. Plotting the isochrones and fitting it on the Cluster
   Isochrones of various ages and different metallicity are obtained from MIST portal[11] using [12]. Fitting of the isochrones is done manually and comparing it with a scipy produced curve fit on the data we get the most fit isochrone.

Results

Images of M13 cluster were taken from [13] in three filters namely 'g','r', and 'i' which have mean wavelengths of 4866$\AA$, 6215$\AA$ and 7545$\AA$ respectively. Figures 2,3 and 4 are the CMD for the respective filters. As expected of a globular cluster most of the stars have left the main sequence and are in the subgiant or red giant phase with hydrogen shell burning. There are a few stars positioned in the bluer region of the HR diagram which may be stars of the horizontal branch, a later phase of the red giant branch.A few stars also exist in the white dwarf region. The image used is not free of field stars and hence there is uncertainty whether the stars of sparsely populated region belong to the same cluster or not.

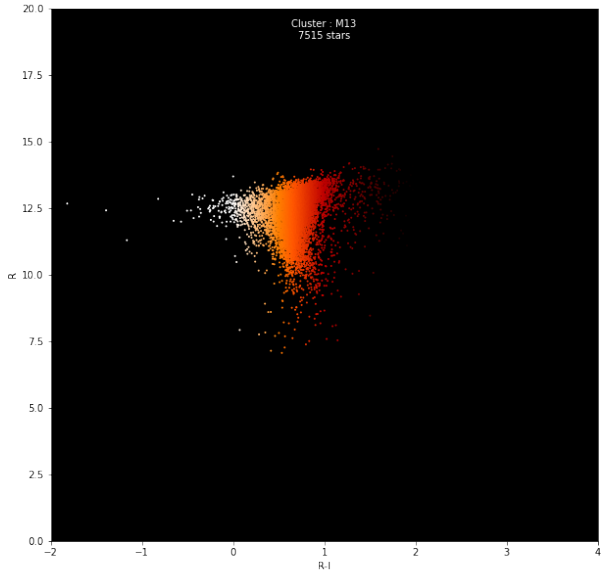

Figure 2: R vs $R - I$

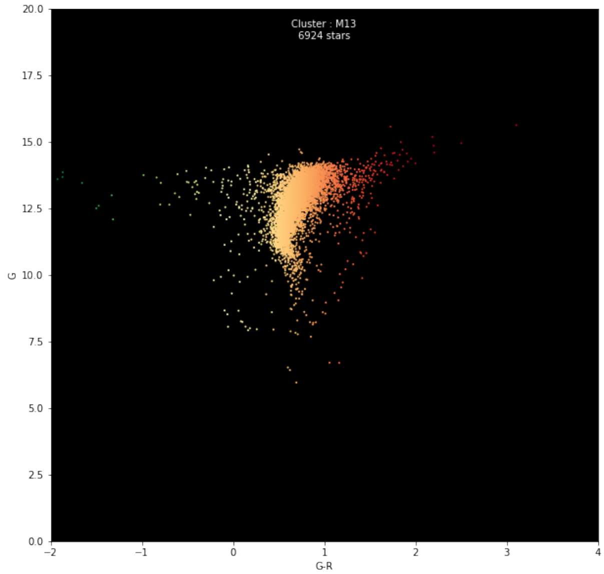

Figure 3: G vs $G - R$

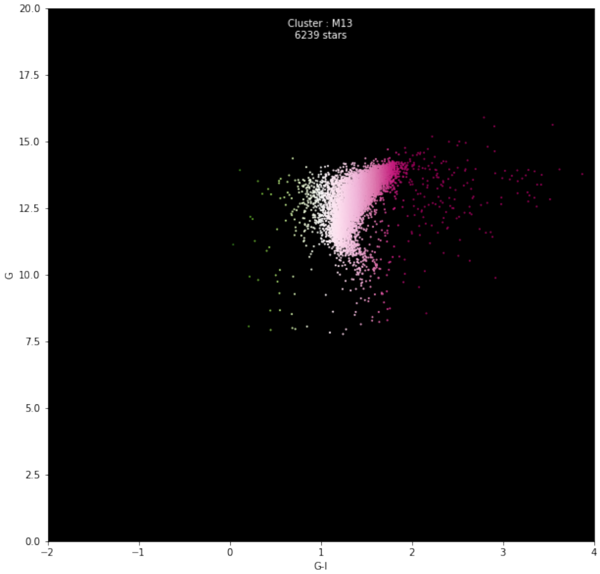

Figure 4: G vs $G-I$

The age of the cluser M13 is $12.00 \pm 0.38 Gyr$[6]. However isochrones for ages greater than $10.6 Gyr$ were unavailable on the MIST portal and hence the estimate obtained can be considered as a lower limit for the age of the cluster. The other parameters that affected the shape of the isochrone was the Fe/H value or the metallicity of the cluster. M13 has a low metallicity of -1.58[6]. But for the obtained data set isochrones of age $10 Gyr$ with metallicity -2 and -4 overlapped very closely and were the best fits available whereas isochrone for $Fe/H = -3$ had missing data in the region of cluster.

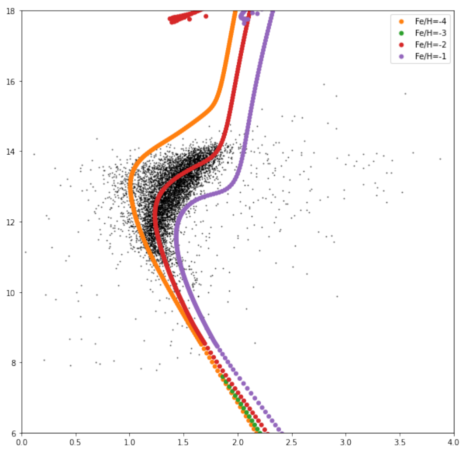

Figure 5: 10 Gyr Isochrones of varying metallicity

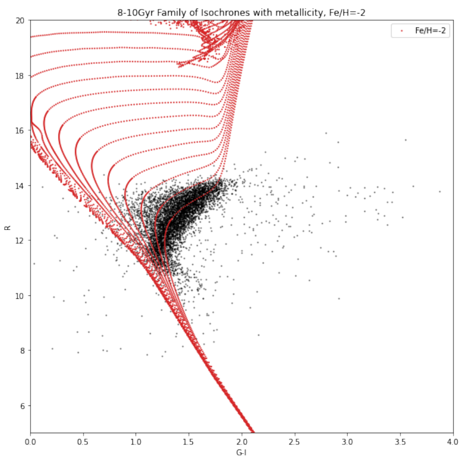

Figure 6: Family of Isocrhones of age 8-10Gyr

Conclusion

This method of isochrone fitting is not the best way to estimate the age of a cluster, especially of older clusters. As one can observe this method is affected by degeneracies such as age-metallicity and age-distance and uncertainties like interstellar reddeining. Hence these contribute to a large error in the final results. There are many studies which have shown better methods to estimate the age of a globular cluster with errors reducing to less than $1Gyr$. This project is a simple demonstration of the traditional isochrone fitting to estimate the age of a cluster and needs rigorous modifications to obtain results comparable to current research.

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