Krittika Summer Projects 3.0

Project Title

Estimating Age of Cluster

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Abstract

In this project, we explored stellar evolution and types of star clusters. Additionally, we performed photometric analysis for star cluster s NGC2509 and NGC5053. FITS data was obtained for both clusters PanSTARRS and GAIA DR3, using which color magnitude diagrams were obtained. Further multiple isochrones were generated and analytically fitted to the color magnitude diagrams and ages and metallicity of the clusters were estimated.

Contents

1

Introduction

A large number of sky surveys and observatories are collecting a huge amount of data to map the sky and observe interesting targets ranging from stars to galaxies far away. Data on star clusters can be obtained from archives, public surveys/observatories and telescopes such as GIT (Growth India Telescope). Using observational data, The astronomical color or color index of the stars can be obtained by performing photometry.

The color index of a star is the difference between the magnitude of the star in one filter and the magnitude of the same star in another filter, using which we can determine surface temperature of the stars. lower the value of color index, Bluer it's color, hotter the star and higher the value, redder it's color, cooler the star. Surface temperature can reveal multiple properties of that star like, its size, mass range, and life span. Let's begin by exploring stars and their classification.

1.1 Stars

A star is a massive sphere of hot gases and plasma, held together by gravitational attraction, balanced and illuminated by nuclear fusion occurring in its core. Typically mass of stars ranges between $0.5 - 8M_0$(solar masses), which is in order of $10^{30} Kgs$. Distributed all across the universe at astronomical distances from the earth, appearing as tiny sparkly objects in night sky. Humans have been observing the night sky for centuries and with technological advancement in recent times, has enable to study these object in details and understand the dynamic process of stellar formation and evolution.

1.2 Classification of Stars

Studying collection of such immense data set becomes complicated unless we order and classify them. To develop a detailed spectral classification system based on the absorption lines they were seeing. They adapted an existing spectral class system which had assigned stars a letter from A to O based on the strength of Balmer series absorption lines.[1]

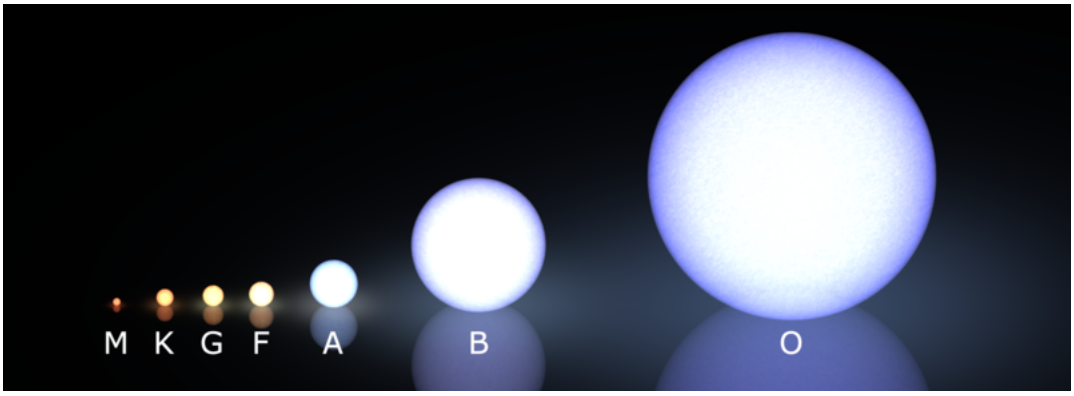


Figure 1.1: Different classes of stars, depicting colour and size (Not to scale)

The new system reordered the classes into the order **OBAFGKM** where "O" stars are the hottest and each successive class is cooler with "M" being the coolest stars. It is to note that, stars near the beginning or end of their lives are not part of this classification.[2]

Spectral Type	Temperature Range (K)	Color
O	>30,000	Blue-violet
B	10,000-30,000	Blue-white
A	7,500-1000	White
F	6,000-7,500	Yellow-white
G	5,000-6,000	Yellow
K	3,500-5000	Orange
M	<3,500	Red-orange

Table 1.1: Classification of star

Our beloved star, Sun with surface temperature $5,778K$, is G-Type(G2V) star. Other well known stars like, Rigel is B-Type star, Sirius A is A-Type star and Betelgeuse is M-Type.

2

HR Diagram

2.1 Star Clusters

A collection of stars, gravitationally bound together, formed from a common huge stellar nebula, containing enough dust and gas to give birth to hundreds and thousands of stars. Stars born in a cluster to share various properties like metallicity, similar masses leading to similar life span, surface temperature and size.[3]

Depending upon the number of stars in a cluster and how strongly the stars are gravitationally bound to each other, we can classify these into 2 categories, open clusters and globular clusters. Exceptions and outliers are found are referred to as intermediate forms.

2.1.1 Open clusters

Open clusters usually contain up to a few hundred members, within a region up to about 30 light-years across. Their population density is low and are loosely gravitationally bound. Due to which they easily get disrupted by other galactic constituents like giant molecular clouds or other clusters, even leading members of cluster to eject. rendering these clusters in an irregular shape.

They are typically young objects with only few million years old. Having less number of members and lower density, they are found in outskirts of a galaxy, being in spiral arms or the edges.

Figure 2.1: Example of a very famous open cluster, pleiades

2.1.2 Globular clusters

Globular clusters are roughly spherical groupings of from 10 thousand to several million stars packed into regions of from 10 to 30 light-years across. Most members of these cluster have had lives a full life, ending spectacularly in a supernova and rest as red dwarf, white dwarfs or other compacts objects.

They can be found close to the center of a galaxy.

Figure 2.2: Example of a globular cluster, M80

2.2 Hertzsprung-Russell Diagram

One of the most crucial tools for studying stellar evolution is the HR diagram, the Hertzsprung-Russell diagram. It was independently develpoed by Ejnar Hertzsprung and Henry Norris Russell in the early 1900s. it plots the temperature of stars against their luminosity, or the colour of stars against their absolute magnitude.[?]

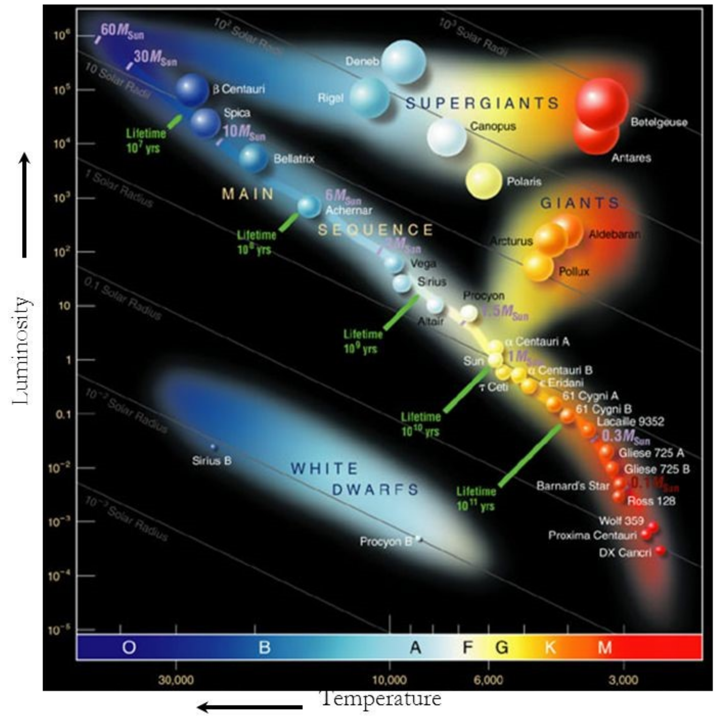


Figure 2.3: Hertzsprung-Russell Diagram

Every star goes through several developmental stages that are determined by its internal structure and method of energy production depending on its starting mass. The temperature and luminosity of the star fluctuate with each of these stages, and as the star develops, it may be seen moving to various areas on the HR diagram.[?]

2.3 Color-Magnitude Diagram

The Colour Magnitude Diagram (CMD) is a representation of observational data that demonstrates how the brightness (luminosity) and colour of a population of stars can be represented (surface temperature). The idea that stars can be thought of as black-body sources, allowing us to employ Wien's Law, provides the foundation for our ability to interpret a star's colour as a measurement of its temperature. Generally, the star's spectral class is plotted on the x-axis (inverted) using this temperature. [8][**?**]

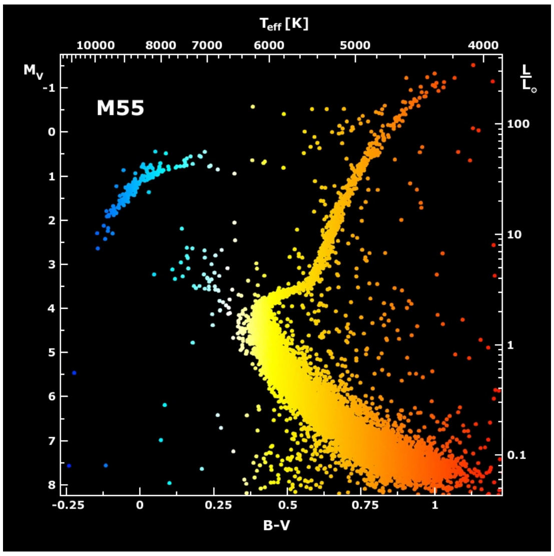


Figure 2.4: Colour Magnitude Diagram

Typically CM diagrams are used rather than HR diagrams, due to their greater practicality. For example

- If the distances to all the stars have been determined, then this might be a plot of B - V versus absolute V band magnitude.
- If the distances to all the stars have not been determined, such as in case for a star cluster, then this might be a plot of B - V versus apparent V band magnitude.

These are both equivalent to plots of luminosity vs. temperature. Near- and mid-infrared measurements can be combined with optical data or used on their own to make CMDs.

3

Photometry and Age Estimation

3.1 Photometry

Photometry is the measurement of the luminance of stars and other celestial objects in astronomy (nebulae, galaxies, planets, etc.). The structure, temperature, distance, age, and other characteristics of the items can all be learned a great deal from such observations.[10]

It's a technique by which we measure the Flux or intensity of the light emited by a source. In other words, it is a method to measure the brightness of sources. We detect photons from the source onto a CCD camera and measure the number of photon collected in a given time. An estimation of photon flux from any particular source gives us its brightness. In astronomy we represents it in terms of magnitude of a source. Magnitude is represented as:

$$m = -2.5 * log_{10}(Flux)$$

Here m is called "instrumental magnitude of a source". As we can see from the formula that it depends on Flux i.e. number of photons collected by camera for a particular source. Number of photons collected by camera greatly depends on its specification and telescope assembly. Hence, this magnitude co-responds to a particular camera assembly. Different cameras may register different Flux for the same source depending on various factors. Hence, the instrumental magnitude may vary with camera. As instrumental magnitude is not a standard thing we cannot use it directly on global scale. Therefore, we have to standardise it. We will do that later. Let's first understand how to estimate the instrumental magnitude.

3.1.1 Aperture Photometry

The measurement of light that enters a specific aperture typically, a circular aperture of a specific size is known as aperture photometry. Which is widely used in photometric analysis of FITS file. Two concentric circles are considered around the source, smaller one covering the entire source point and outer circle covering small outside area. The area between the circles calculate the noise and subtract it from the source or the flux value of the source to get precise measurements. This technique helps us to get intensity of the source in particular band, which obtains for multiple bands can reveal interesting information.[11]

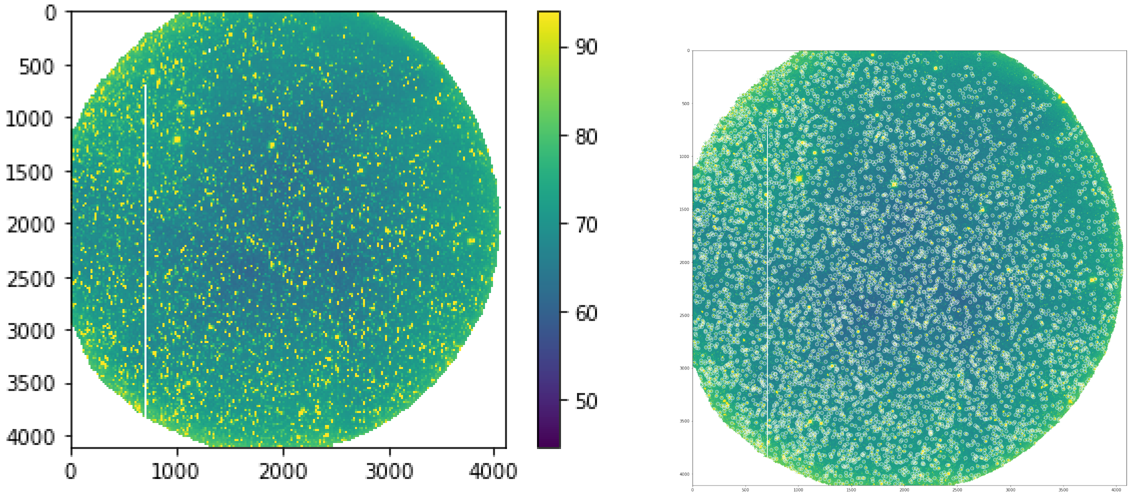


Figure 3.1: a) Image of a star cluster b) Identifid sources for aperture photometry

3.1.2 PSF Photometry

We take Point Spread Function (PSF), or instrumental Point Spread Function to be the infinite resolution and infinite signal-to-noise flux distribution from a point source on the detector, after passing through optics, dust, atmosphere, etc. In colloquial usage PSF photometry sometimes refers to the more general task of model-fitting photometry, regardless of exactly what kind of model is actually being fit. This technique helps in source identification as well as in determining intensity of that particular point.

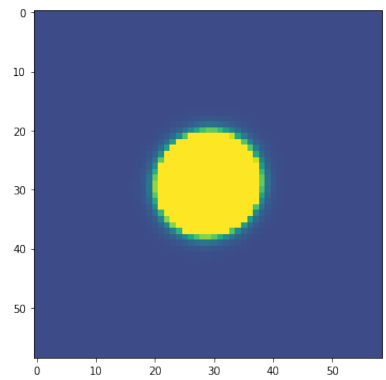


Figure 3.2: Identified Point Spread Function for a source

3.2 Age Estimation

We can learn a lot from star clusters that is applicable to the study of stars in general. The fundamental justification for this is because all of the stars in a cluster are thought to have formed practically simultaneously from the same cloud of interstellar space, therefore they should all have extremely similar characteristics. Accordingly, the sole distinguishing factor among stars in a cluster is their mass, and if we measure the characteristics of one star (such as its age, distance from us, composition, etc.), we may infer that the characteristics of the other stars in the cluster will be strikingly similar.[7]

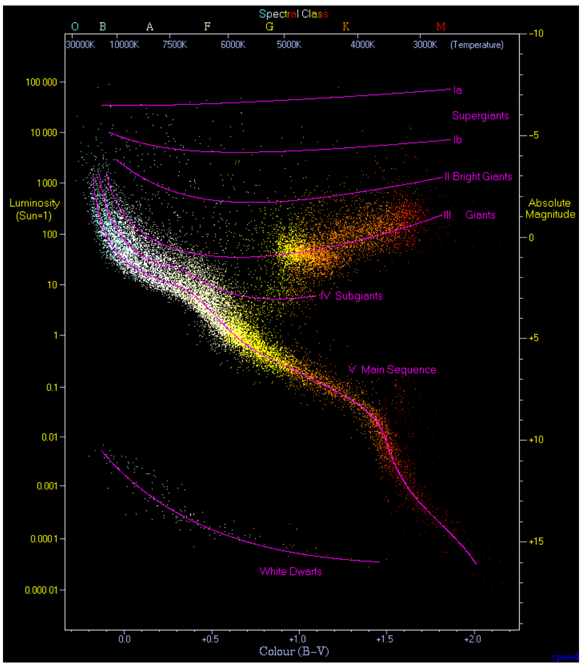


Figure 3.3: Isochrones with HR Diagram

As the stars in the cluster evolves, it shifts and move around various regions in color magnitude diagram. And thousands of evolving stars with similar composition but different masses starts to create a pattern, which studied carefully can replicated as well. For a give initial condition/parameters these evolutionary curves can be predicted for a particular age. These curves giving evolutionary information for a group of stars with similar composition which can be used to estimate their age are called isochrones.[6]

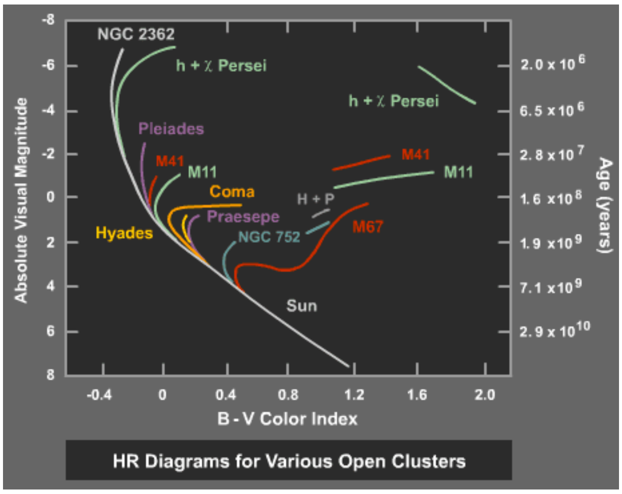


Figure 3.4: Isochrones

4

Data Analysis

4.1 Data pre-processing

All the raw images captured by a telescope has to go through some fundamental pre-processing. This is necessary to eliminate the noise created by atmosphere/sky, detector noise, cosmic or some other phenomenon. System and source information is linked with the data as soon as it is recorded, which helps in further processing.
For photometry data from optical and closely nearby region from electromagnetic spectrum is used. Usually images taken in B, V, and I bands. Basic reduction of a image consist of correcting for bias and flat frames.

4.1.1 Bias

Multiple images are captured with the closed aperture, so no external light reaches the detector. One expects these frames to be completely dark, but due to some or other error, we get to see that not all pixels have zero value. Some pixels are more sensitive than others and register even the faintest of the signal and other doesn't, These are called hot pixels.

Telescopes observing in near-infrared or infrared wavelengths has to be very cautious about this, as even with closed aperture, oversensitive CCDs pixels can register heat radiated(in infrared wavelengths) from the telescope's equipment.

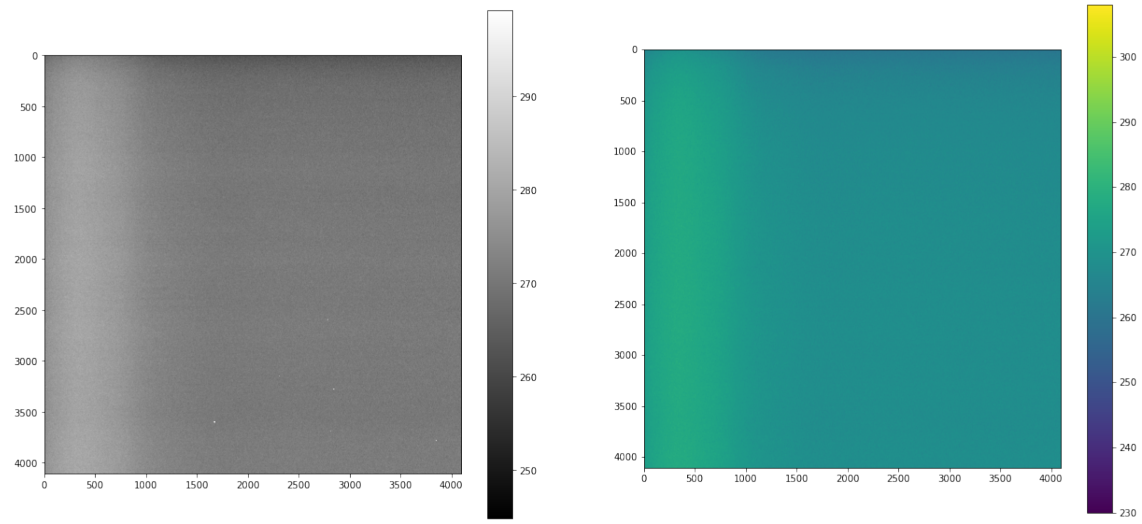


Figure 4.1: a) Bias Frame b) Master Bias Frame

4.1.2 Flat

Another Important thing to keep in mind is to take a flat frame before starting the observation. A flat frame is to capture the darkest area of sky, multiple times and average it over, creating a master flat frame. This helps in eliminating atmospheric noise and other optical aberrations.

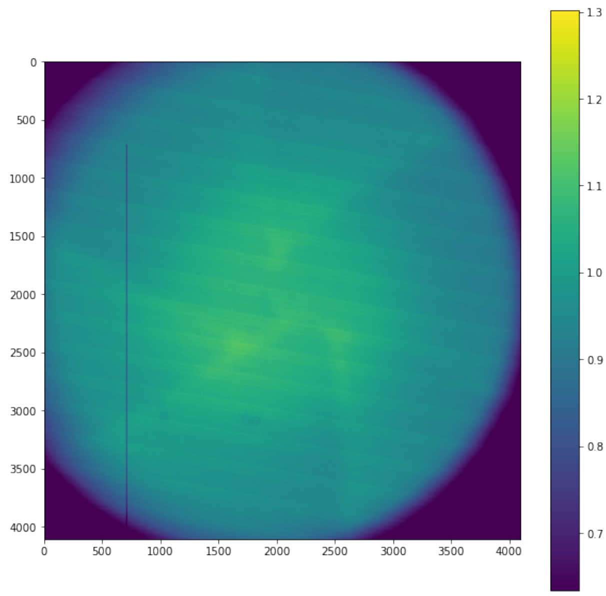


Figure 4.2: Flat Frame

4.1.3 Reduced Data

After getting bias and flat frames, we start our observation run. The images taken then get pre-processed and the master bis and master flat frames are subtracted from the obtained image. Below is the sample for reduced images, captured by the GROWTH India telescope.

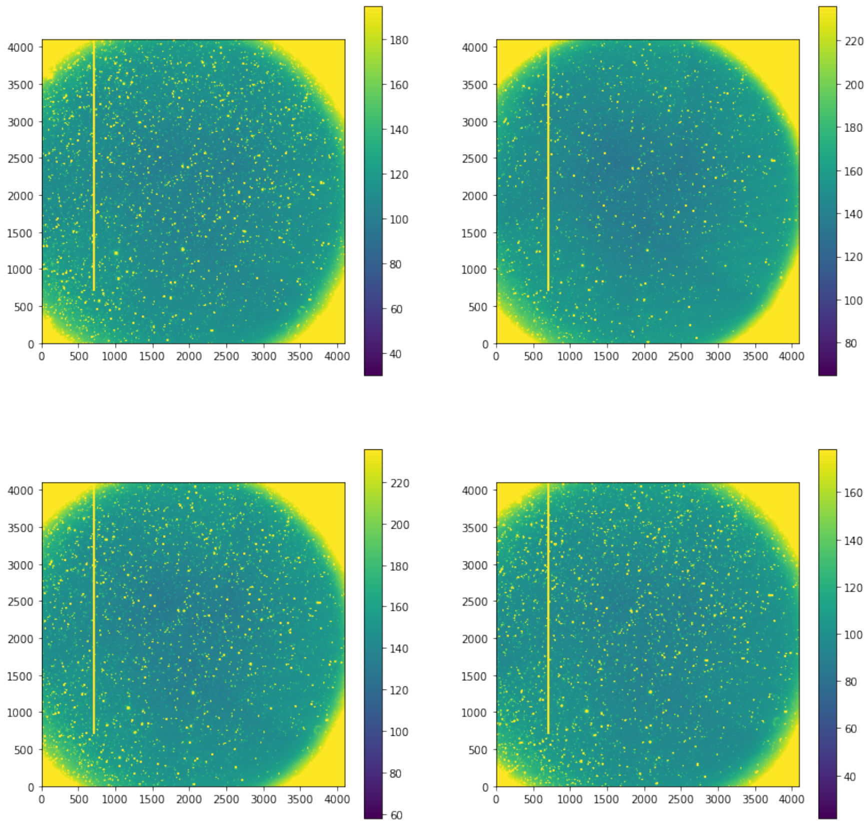


Figure 4.3: Reduced Images

4.2 Data Collection

This project uses images from PanSTARRS [12] archive and Data from Gaia DR3 [15] (epoch 2016).

4.2.1 PanSTARRS

The Panoramic Survey Telescope and Rapid Response System (Pan-STARRS1) located at Haleakala Observatory, Hawaii, US, consists of astronomical cameras, tele-

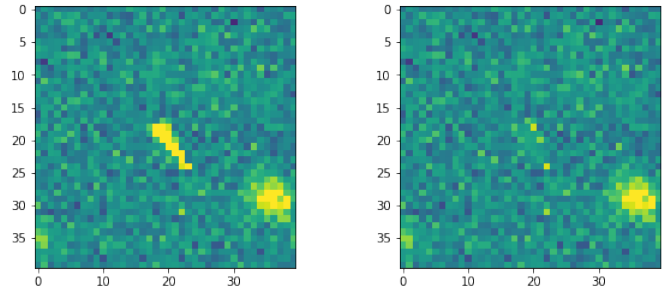


Figure 4.4: a) With possible Cosmic ray damage b) Removed Cosmic ray

scopes and a computing facility that is surveying the sky for moving or variable objects on a continual basis, and also producing accurate astrometry and photometry of already-detected objects.

Data was obtained from PanSTARRS-1 Image Access. "FITS-Cutout" images of "Auxiliary data" in "stack" file type, for "g", "r" and "i" bands with "6000 pixels" (1500.00 arcsec) were downloaded for NGC2509 and NGC5053 clusters.[**?**]

4.2.2 CDS Xmatch

The CDS cross-match service is a tool allowing astronomers to efficiently cross-identify sources between astronomically large catalogues or between a user-uploaded list of positions and a large catalogue.[14]

To eliminate the contamination of field stars in the FITS files, we decided to use CDS Xmatch to obtain a better catalogue of the stars in the given clusters. For which data from "Gaia DR3 (Epoch 2016)" and "PanSTARRS DR1" were selected, with Cross-match criteria of radius "5 arcsec" and conical area of radius "25 arcmin" was downloaded.

4.3 Photometric Analysis

We have used various python libraries including Astropy, Photutils, and Astroquery. Additional astrometic software SExtractor and PSFEx. These softwares are comatible to IOS and linux only. Hence to be able to use them on widows, Windows Subsystem for Linux (WSL[1]) was installed, It is is a compatibility layer for running

[1] `https://learn.microsoft.com/en-us/windows/wsl/install`

Linux binary executables natively on Windows 10, Windows 11, and Windows Server 2019. To being with, we start by reading the data from the downloaded FITS file and crop the data accordingly.

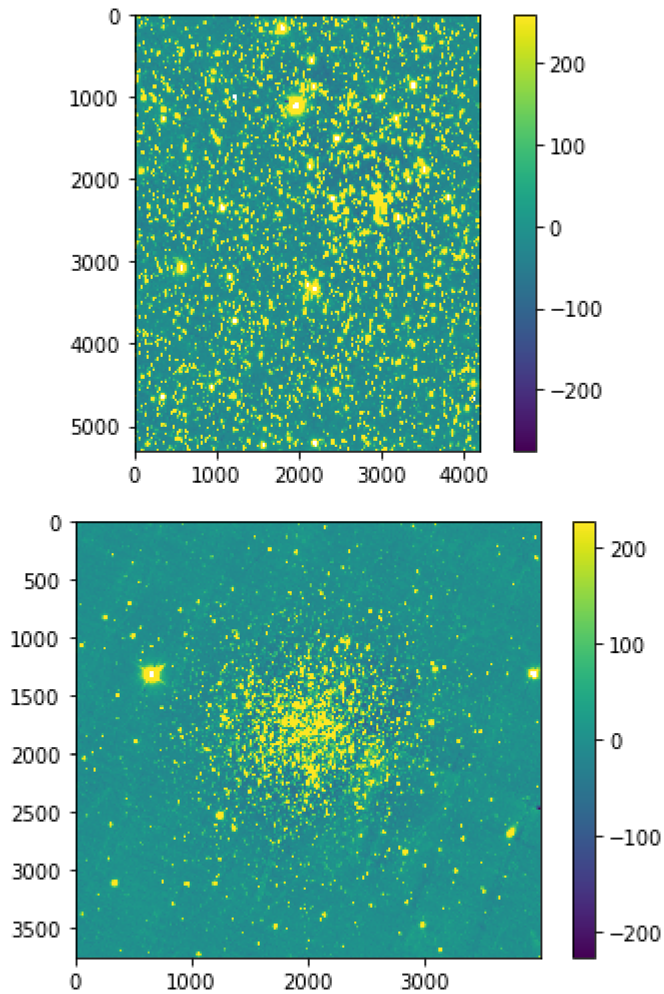


Figure 4.5: FITS data a) NGC 2509 b) NGC 5053

Configure and parameters were set for to extract sources using SExtractor. This software is widely used by Astro community for detecting sources from a fits images. Its sources detection methods has been trained on various telescope images and are quite reliable. Then good sources were selected from the obtained sextractor catalogue.

These sources are then filtered according to their brightness and further crossed match to Vizer database based on their RA and Dec to get a new catalogue we termed as "good_stars". Vizer database has various catalogues in multiple range of wavelengths and from different mission around the world. Similarly, using sextractor we did PSF photometry to obtain a catalogue with fluxes of each sources in the FITS files.

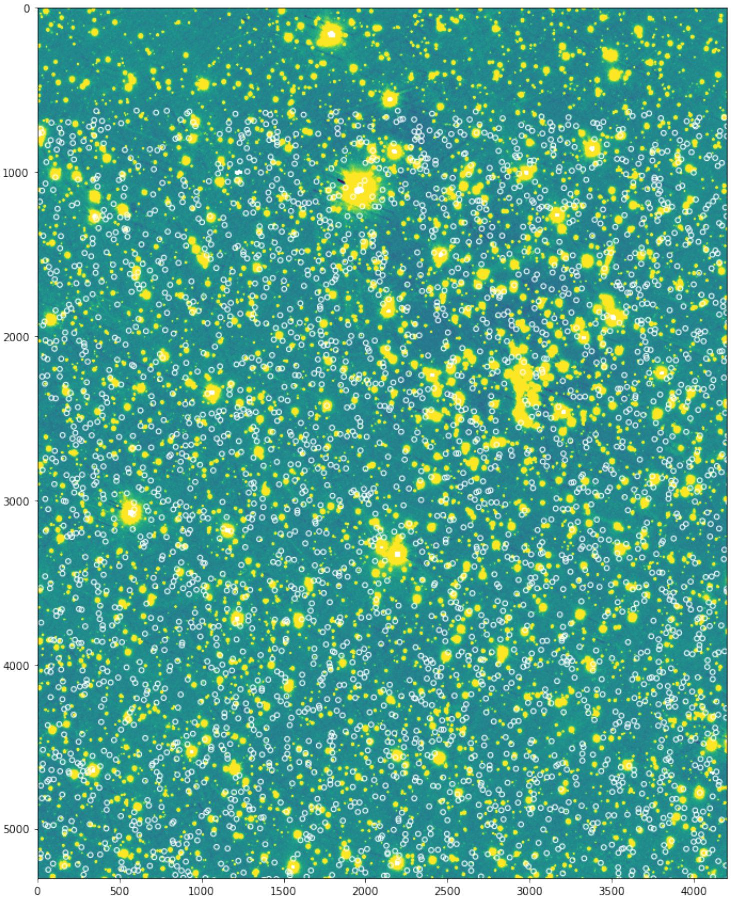


Figure 4.6: Source detection in NGC 25209

Now, we had few options from which we could plot a color magnitude diagram.

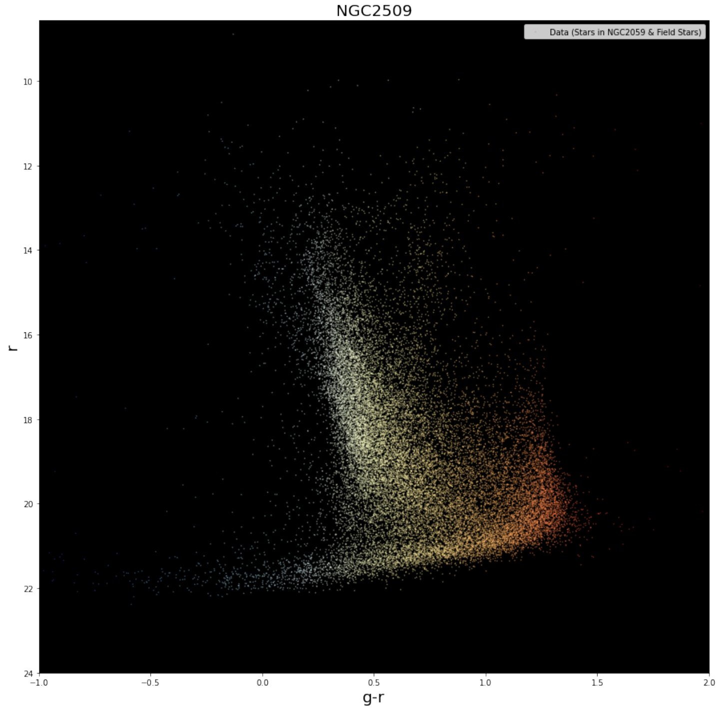
1. We could use the "good_stars" catalogue, which has magnitudes in g, r and i bands.
2. We could perform PSF photometry on all three FITS file we downloaded from PanSTARRS. Then cross match all the stars with different fluxes obtained in different bands then use it to plot a CMD.
3. We also had data from CDS Xmatch, containing magnitudes of stars in G, BP, and RP bands.

We used (1) method as it was querying from a reliable database. But we were still getting contamination from the filed stars which was hindering in estimating the age of the cluster. This worsen in the case of open cluster NGC2509, where the distinction between cluster members and field stars was not visible. To rectify this problem, one can calculate membership probability for each star in the cluster and choose the stars with higher than thresh hold value. Instead we opted the (3) method, which was way more elegant and helped us getting better results.

4.4 Isochron fitting

"Ezmist" python module was used to generate theoretically isochrones with various initial parameters like like and metallicity. This package provides a direct interface to the MIST/MESA isochrone webpage [16]. It compiles the URL needed to query the website and retrives the data into a python variable.

Multiple ischorones with a range of ages and metaliity were generated and fitted to the obtained CMD. These fits were analytically fitted with slight positional adjustments.



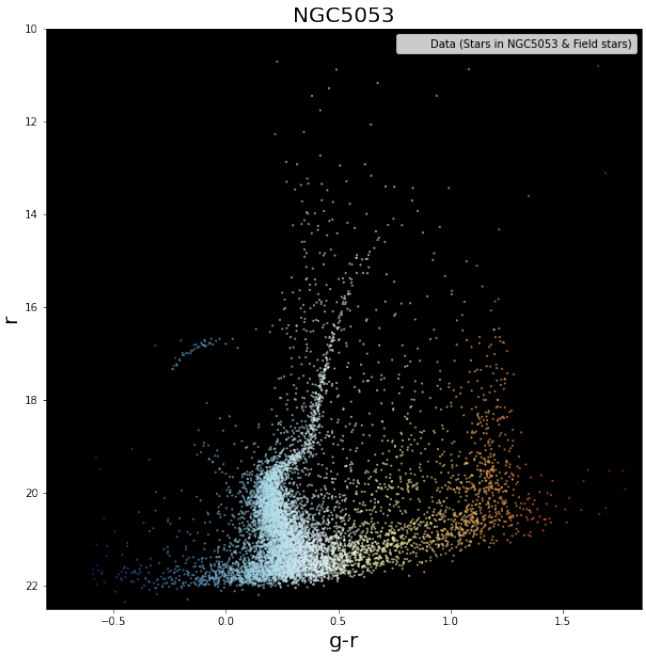


Figure 4.7: CMD for a) NGC 2509 b) NGC 5053 with g-r value on x-axis, r magnitude on y-axis and colour of the stars represents relative surface temperature with blue being the hottest and red being the coldest. g mag and r mag values were obtained from aperture photonmerty of FITS file data.

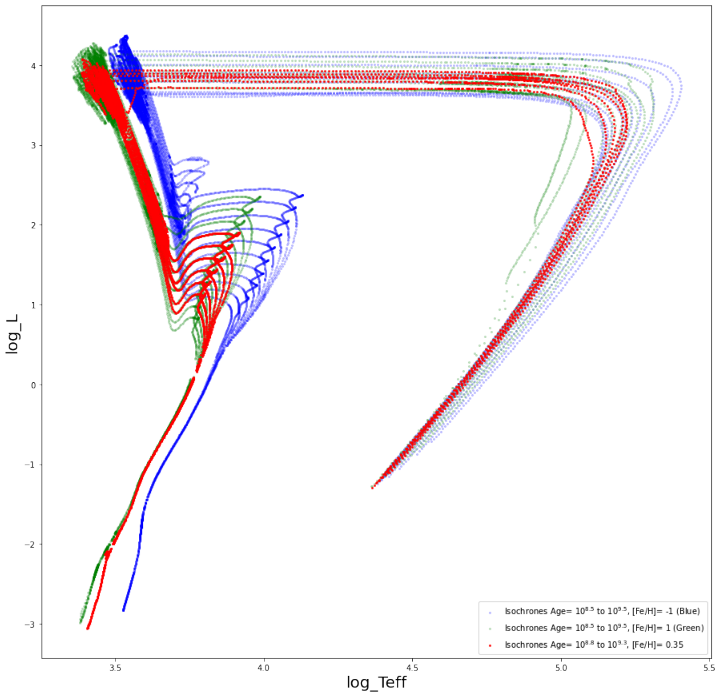


Figure 4.8: Simulated isochrones for ages $10^{8.8}$ to $10^{9.3}$ for metallicities -1, 0.35 and 1.

5

Results and Conclusion

5.1 NGC 2509

NGC 2509 is an open cluster in the constellation of Puppis.[18]

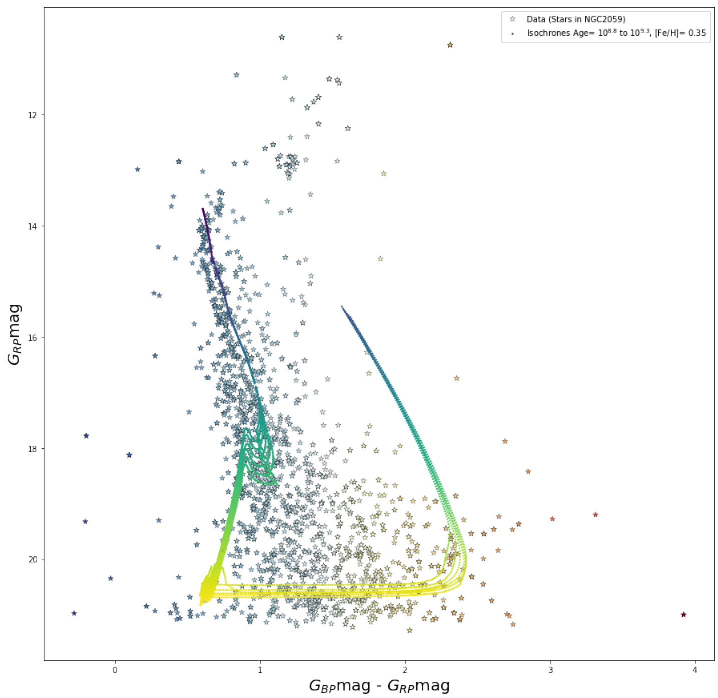


Figure 5.1: Isochrones fitted CMD for NGC 2509, with data from CDS Xmatch

5.2 NGC 5053

NGC 5053 is the New General Catalogue designation for a globular cluster in the northern constellation of Coma Berenices.[20]

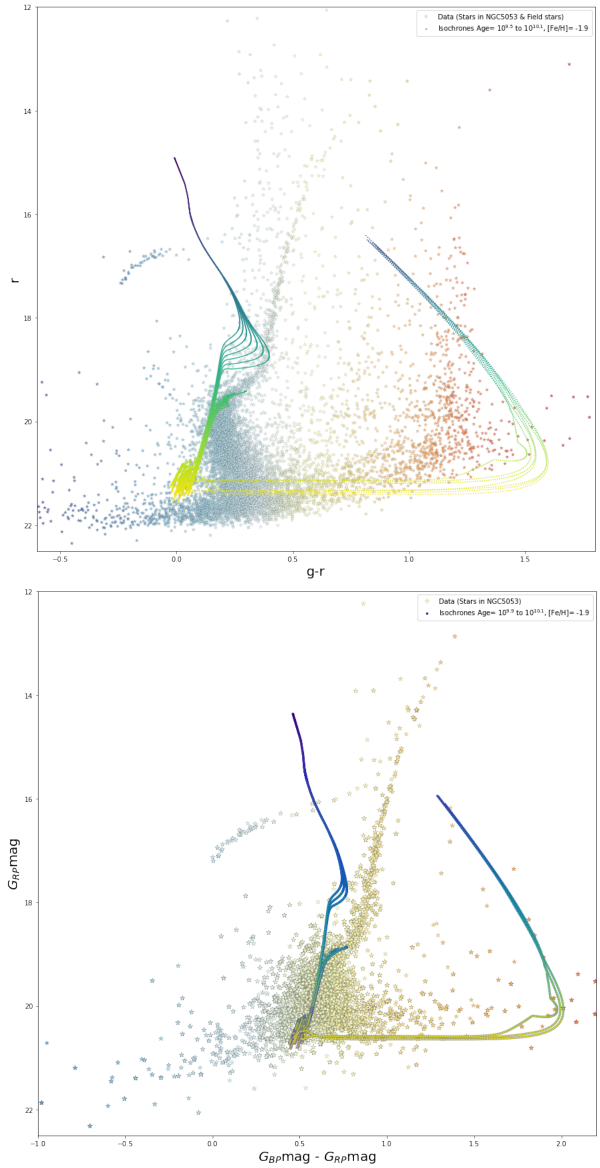


Figure 5.2: Isochrones fitted CMD for NGC 5053, with data from a) FITS file analysis b) CDS Xmatch.

Cluster	**Estimated Age** (Gyr)	**Estimated Metallicity**([Fe/H])
NGC 2509	1.31 ± 0.6	0.35
NGC 5053	10.26 ± 2.3	-1.9

Table 5.1: Results

5.3 Conclusion

As 5.1 shows, Estimated age for NGC 2509 comes out to be in between $10^{8.8}$ to $10^{9.3}$ (0.6 to 1.99Gyr) and Its metallicity ([Fe/H]) equals to 0.35, which is very close to the recently calculated[17] age and [Fe/H] of $10^{9.2037}$ (1.58Gyr) and 0.3469 respectively.

Similarly for NGC 5053, we estimated its age from $10^{9.9}$ to $10^{10.1}$ (7.94 to 12.58Gyr)and [Fe/H]= -2.3, that is verified by latest studies[19] showing its age to be $10^{10.096}$ (12.52.0Gyr) and metallicity be -1.9.

5.4 Discussion

We can further extend this work to get even more precise results, by going deep into data processing and use advanced methods to filter our FITS file, working on membership probability, isochron generation and fitting.

These techniques if perfected, can be used to extract additional intriguing information related stars in clusters and other astronomy sub-fileds which requires photometric analysis.

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