Krittika Summer Projects 2023

Gaia Data Analysis

Aditya Saran, Aryan Kumar, Vasudev Dubey, Tushar Kumar Jain, Saumya Aryan, and Vaibhav Jethwani

Aditya Saran[1,2,3], Aryan Kumar[1,2,3], Vasudev Dubey[2], Tushar Kumar Jain[2], Saumya Aryan[2], and Vaibhav Jethwani[2]

[1]Krittika - The Astronomy Club of IIT Bombay, Powai, Mumbai - 400076, India

[2]Indian Institute of Technology Bombay, Mumbai - 400076, India

[3]Mentors of the project

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Abstract

Gaia is a space observatory of the European Space Agency (ESA) which was launched in 2013 and expected to operate until 2025. It aims to build the most accurate map of our galaxy so far, by mapping the positions, distances and proper motions of the stars with enormous precision. It currently operates around the Sun-Earth L2 Lagrangian point.

All of Gaia's data is accessible publicly via ADQL interface on Python, using the package `astroquery.Gaia`. This allows us to study the astrometric and certain photometric characteristics of over a billion stars upto magnitudes of 21 in the Gaia catalog using our computers. The Gaia Data Release 3 was released on 13 June 2022.

This project aims to use the data for specific types of stars, and then to use the trends observed to arrive at some interesting qualitative results for those chosen stars.

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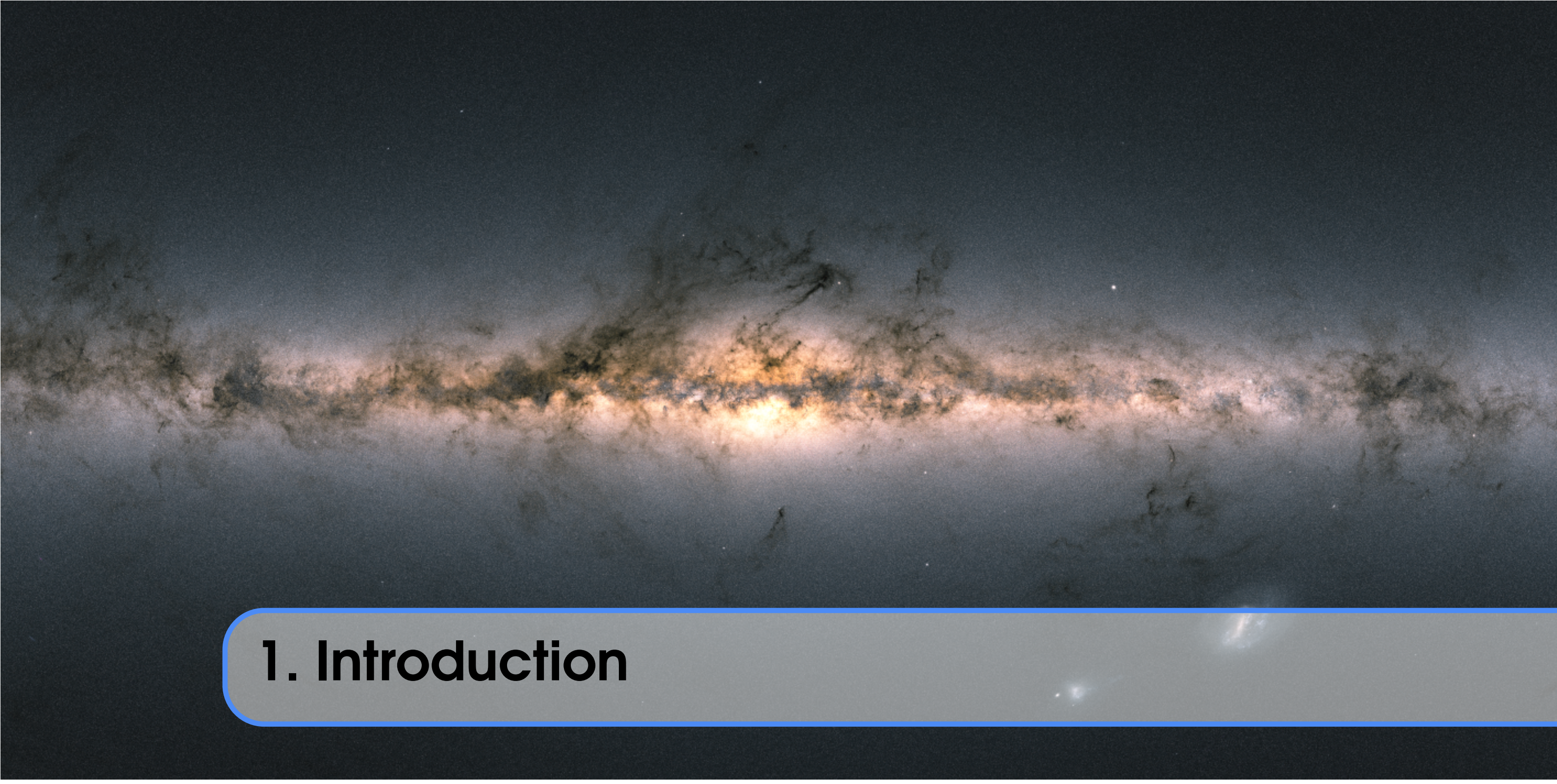


1. Introduction

1.1 Collecting Data

Gaia will perform its observations from a controlled Lissajous-type orbit around the L2 Lagrange point of the Sun and Earth-Moon system. During its 5-year operational lifetime, the satellite will continuously spin around its axis, with a constant speed of 60 arcsec/s. As a result, over a period of 6 hours, the two astrometric fields of view will scan across all objects located along the great circle 'perpendicular' to the spin axis. As a result of the basic angle of $106.5°$ separating the astrometric fields of view on the sky, objects transit the second field of view with a delay of 106.5 minutes compared to the first field.

Gaia has two telescopes with a fixed angular separation of $106.5°$. Both of them rotate at the same angular velocity around an axis perpendicular to line of sight of the two telescopes. Light from both telescopes are focused onto a plane of CCDs using a mirror. The CCD array has 106 individual CCDs, and almost 1 billion pixels.

When light from the first telescope falls onto the CCD array, the first line of CCD is activated and selects the stars from the first telescope to be projected on the main CCD grid. Similarly for the second telescope, the second CCD line is activated.

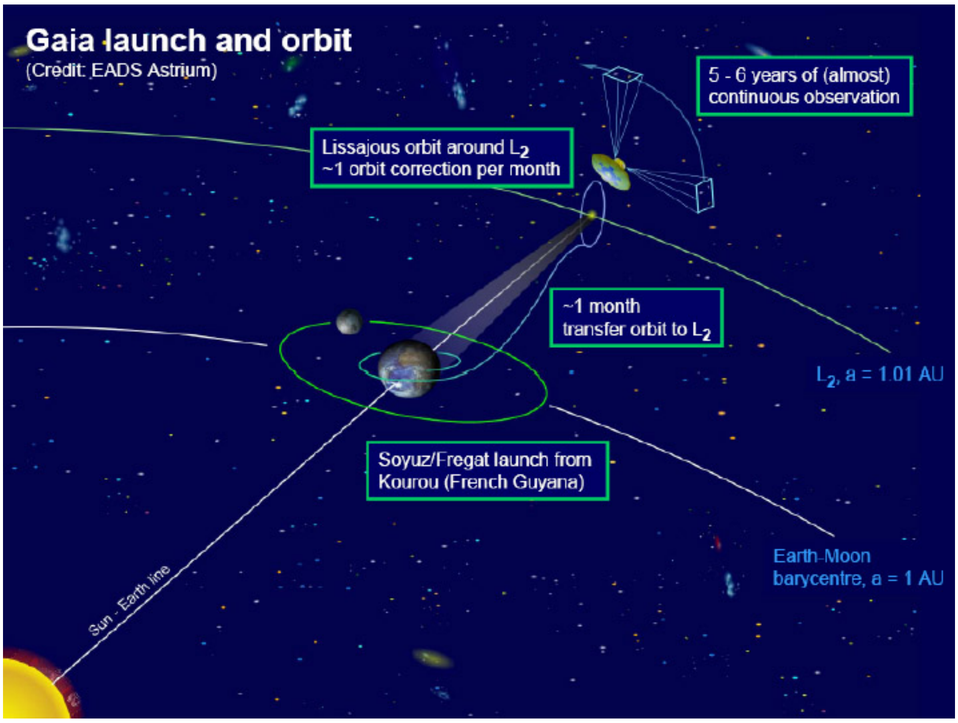


Figure 1.1: Orbit of Gaia around Sun-Earth L2

As the telescope rotates, light from each single star moves across the CCD grid. There are three main measurements made:

1. The first grid of pixels is the *astrometric field*. It tracks the position of the star. As the star moves along each CCD in the CCD grid, the on-board computer finds out its position using the CCD pixels and also finds out its brightness. As the starlight passes through the 9 columns of CCD, each column measures its position and brightness. Multiple measurements help to minimize the error, and also optimizes the amount of data needed to be sent.
2. The next two columns are meant for photometry. Light from the stars is passed through two special prisms, that directs the smaller and larger wavelength components of the star's light onto the blue and red photometers respectively. This provides information about the star's temperature (Wien's law), size and chemical composition (relative abundance of hydrogen, helium etc. using intensity of their spectral lines).
3. Light from the brighter stars is captured on the radial velocity spectrometers, which measure the stars' radial velocity using Doppler effect (using hydrogen spectral lines as the base wavelength).
4. Additionally, as Gaia moves along with Earth around the Sun, it also records each star's parallax, thus allowing us to find the distance to that star.

The collected information from the CCDs is compressed into a data packet to be stored on Gaia's onboard computer. and later transmitted back to ESA's ground stations. This process is repeated for each star as the telescopes rotate. Around 3 million stars are measured every hour. Gaia maps over a billion different stars, upto a limiting magnitude of about 20, and would thus catalogue about 1% of our galaxy's stars. It is also expected to trace numerous asteroids and comets in our Solar System, exoplanets, brown dwarfs, supernovae and quasars - apart from numerous stars from other galaxies (Magellanic Clouds and farther in the Local

Group). Each star is mapped almost 70 times over the course of 5 years before the processed data is released.

1.2 Coordinate Systems

1.2.1 Galactic coordinate system

The **galactic coordinate system** is a celestial coordinate system in spherical coordinates, with the **Sun** as its **center**, the primary direction aligned with the approximate center of the Milky Way Galaxy, and the fundamental plane parallel to an approximation of the galactic plane but offset to its north. It uses the right-handed convention, meaning that coordinates are positive toward the north and toward the east in the fundamental plane.

Galactic longitude:
Longitude (l) measures the angular distance of an object eastward along the galactic equator from the galactic center. Analogous to terrestrial longitude, galactic longitude is usually measured in degrees(°).

Galactic latitude:
Latitude (b) measures the angle of an object northward of the galactic equator (or midplane) as viewed from Earth. Analogous to terrestrial latitude, galactic latitude is usually measured in degrees(°).

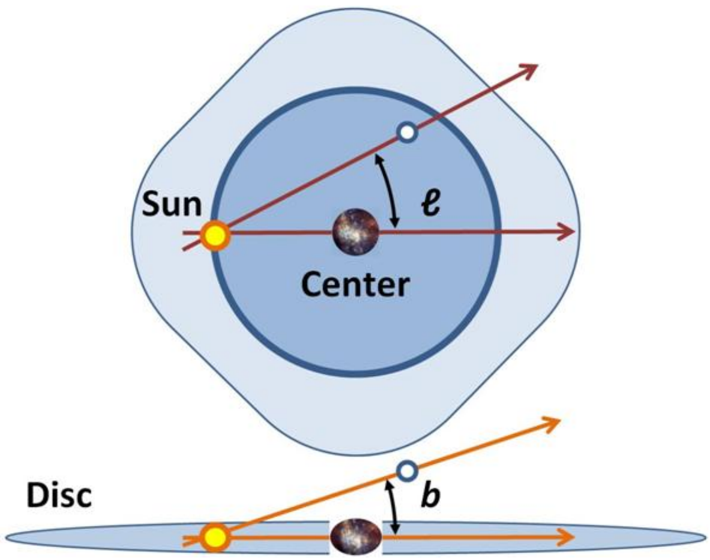


Figure 1.2: Galactic coordinate system

Here, in the from the above figure we can see that the galactic longitude is measured from the line joining the sun and galactic center and it is represented as l.

Similarly, latitude is measured above the galactic equator or midplane and it is represented by b.

1.2.2 ICRS coordinate system

- The **International Celestial Reference System (ICRS)** is the current standard celestial reference system adopted by the **International Astronomical Union (IAU).**
- Its origin is at the **barycenter** of the **Solar System**.
  Barycenter is the center of mass of two or more bodies that orbit one another and is the point about which the bodies orbit.
  Unlike galactic coordinate system (which has sun as origin), ICRS has barycenter of solar system as origin.

1.3 Photometry

1.3.1 Flux

Luminosity: Luminosity is the energy released by a star in one second. It is generally denoted as L.
Flux is defined as:-

$$F = \frac{L}{4\pi r^2}$$

where r is distance of star from earth

1.3.2 Magnitude scale

Apparent magnitude

The stars' are classified on the basis of their apparent magnitude using the magnitude scale.
Apparent magnitude is defined as:-

$$m = -2.5\log_{10}\left(\frac{F}{F_0}\right)$$

here, F_0 is the reference flux of a source of our choice. Since the negative log is used in the definition, stars with higher magnitude values are fainter. The brightest object in the sky, the Sun, has an apparent magnitude of -26.74. The brightest star, Sirius, has an apparent magnitude of -1.46. The star Vega was historically assigned the baseline apparent magnitude of 0.00, but this was further refined later with other definitions when Vega was discovered to have slight variations in its luminosity.

Absolute magnitude

The apparent magnitude of a star is good enough to tell us about its brightness as seen from Earth, but it does not tell us anything about its intrinsic luminosity i.e. the total energy it radiates, due to the distance factor in the flux. So we use the absolute magnitude, which is the magnitude of a star as seen from a distance of 10 parsecs (1 parsec = 3.26 light years). By comparing the absolute magnitudes of two different stars, we directly have a measure of their luminosities as the distance factor cancels out.

$$M = m + 5 - 5\log_{10} r$$

where r is the distance of the star from Earth in parsecs.

1.3.3 Using filters

Red pass filter

This filter allows higher wavelengths to pass through and blocks the lower wavelengths. The flux is available in the form of red pass apparent magnitude, denoted as G_{RP}.

Blue pass filter

This filter allows lower wavelengths to pass through and blocks the higher wavelengths. The flux is available in the form of blue pass apparent magnitude, denoted as G_{BP}.

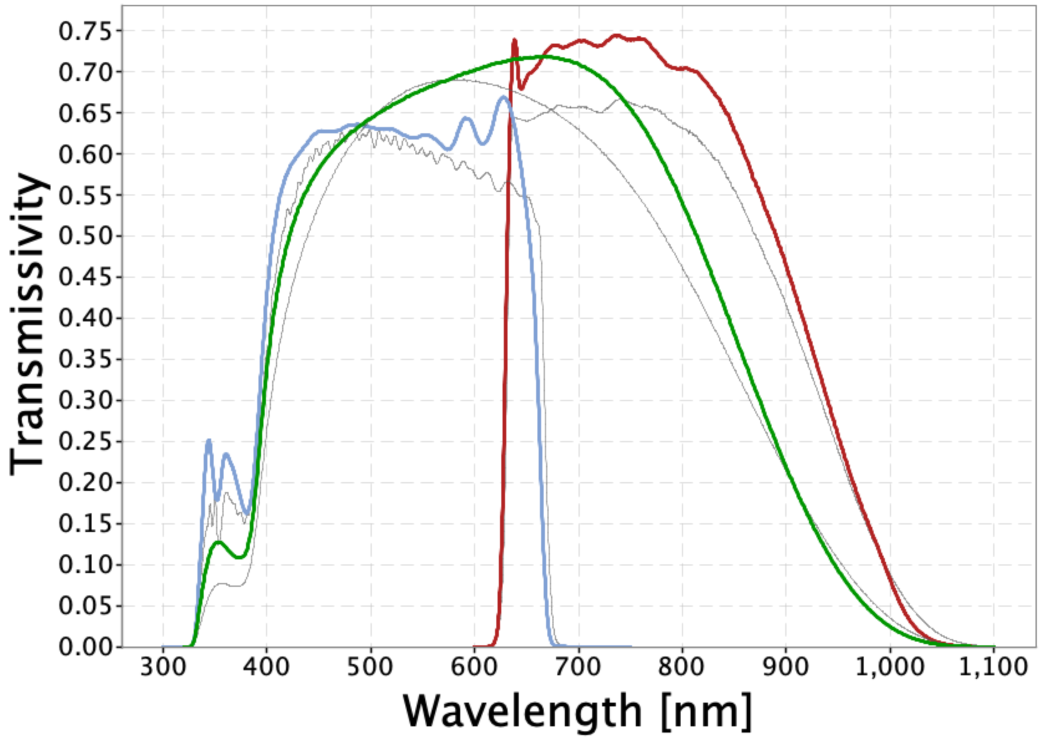


Figure 1.3: Range of Wavelengths admitted by each passband - red is for red pass filter, blue for a blue pass and the green line denotes the entire flux in visible range

1.4 Astrometry

1.4.1 Parallax

Parallax measures the angular movement of a star w.r.t. a fixed background of the sky. The angular movement is a result of the Earth (and Gaia) revolving around the sun. From different points in the orbit, the line of sight to the star is slightly different resulting in parallax. It has units of angle. The unit of distance parsec is defined as the distance at which a star appears to have a parallax of 1 arcsecond (1/3600 of a degree) as seen from Earth.

Hence, parallax p of a star is directly related to its distance d as d in parsecs $= \frac{1}{p}$ where parallax is in arcseconds.

1.4.2 Proper Motion

A star also has its intrinsic relative velocity w.r.t. Earth-Sun system due to its motion around the galactic center. This results in the star changing its position in the sky by a very small amount each year, known as proper motion. Note that the proper motion only measures the transverse component of the star's velocity, or more precisely, its angular velocity w.r.t. Earth. The transverse component of velocity is not included. Proper motion in Gaia catalogs is measured in milliarcseconds/year.

1.5 HR Diagrams - the Physics of Stars

A star can be approximated quite well as a blackbody. For the same, we have the typical radiation curve and Planck's Law as show below

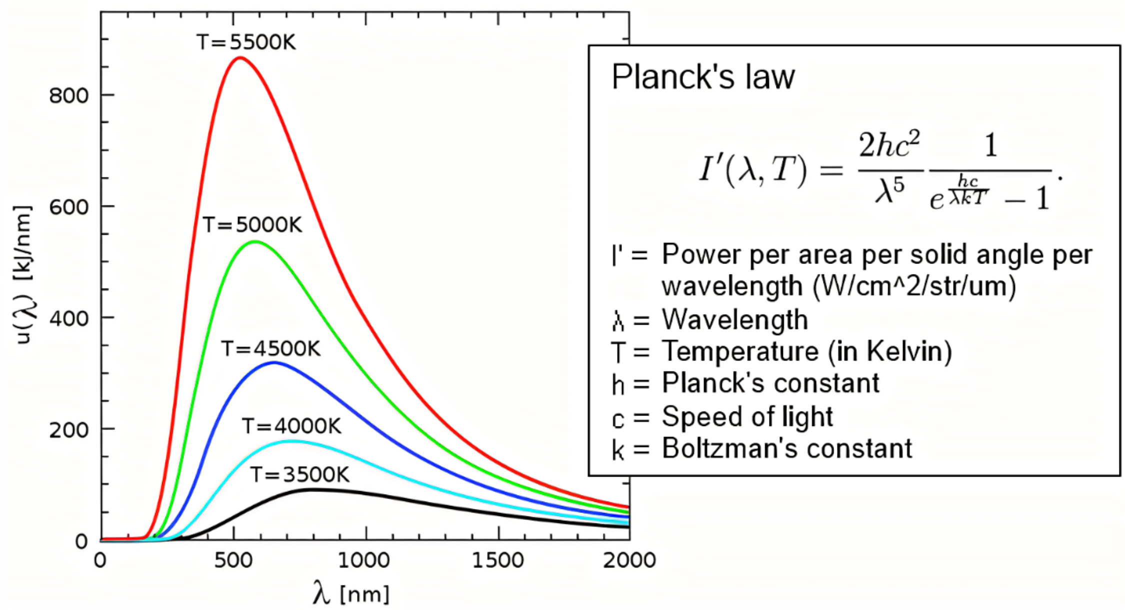


Figure 1.4: Blackbody Radiation Curve

It is easily seen that as temperature increases, the peak shifts to the left. Now consider this with respect to the blue pass and red pass filters. At a lower temperature, there is more flux from stars at higher wavelengths i.e. in the red band. So G_{RP} is lower in value than G_{BP} or $G_{BP} - G_{RP}$ is more positive. The opposite happens for higher temperature stars, i.e. $G_{BP} - G_{RP}$ is less positive or negative. So if we plot $G_{BP} - G_{RP}$ on one axis, it gives a good idea of the temperature.

Meanwhile, consider the flux-luminosity relation given by

$$F = \frac{L}{4\pi r^2}$$

and the absolute magnitude

$$M = -2.5\log_{10}\left(\frac{F}{F_0}\right) = -2.5\log_{10}(L) + c$$

where c is a fixed constant. Thus absolute magnitude serves as a measure of luminosity.

Finally, it may be noted that luminosity is related to surface temperature as

$$L = 4\pi\sigma R^2 T^4$$

where R is the radius and T the surface temperature of the star.

1.5.1 HR Diagrams

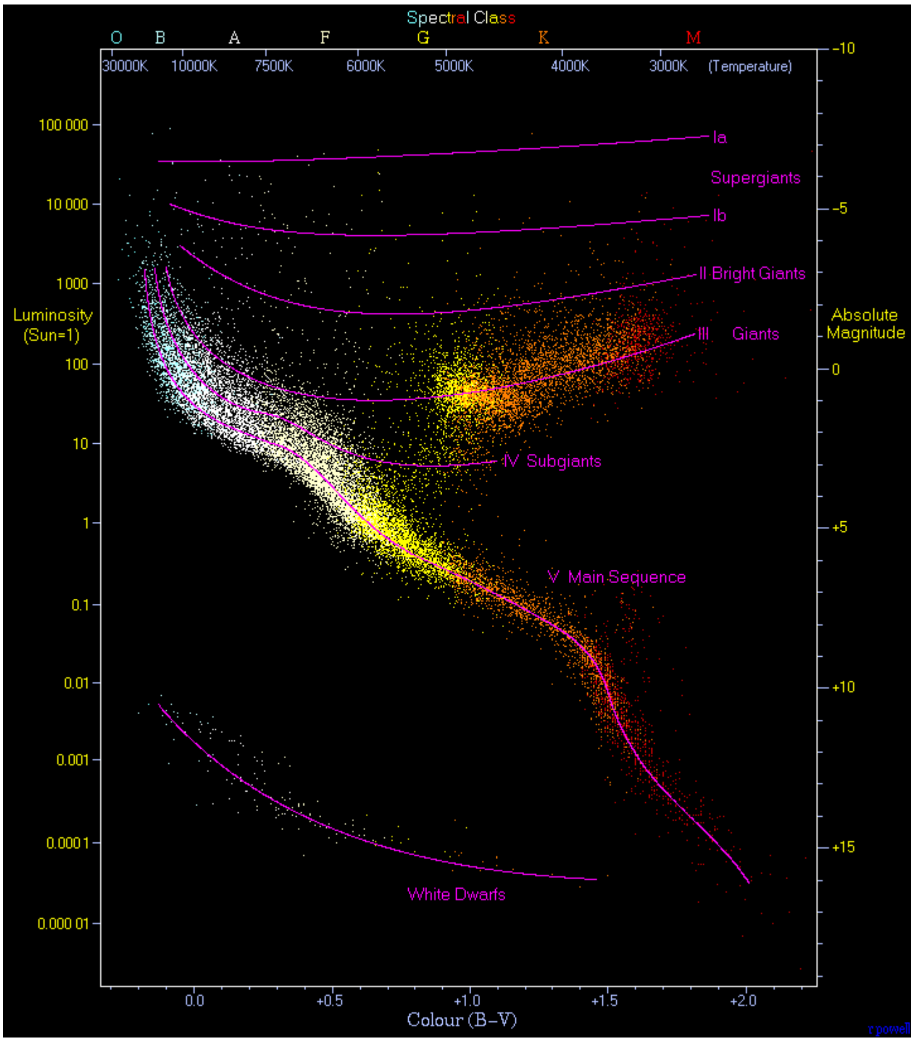


Figure 1.5: Standard HR Diagram

Normally, one would expect there to be no relation between the luminosity (absolute magnitude) and temperature ($G_{BP} - G_{RP}$) due to the radius of a star being a uniformly varying value. However, the internal structure of the star (mainly its mass) dictates that only specific combinations of these are allowed, which was deduced by studying stellar data extensively. These are shown on the Hertzsprung-Russell diagrams (HR diagrams) which look something like above.

Most of the stars in a cluster occupy a region called the main sequence. These are stars that are using hydrogen as their fuel. The main sequence can be divided into classes as follows.

Spectral Classification

Each star is divided into different spectral types depending on the spectrum produced by the star. Further, each spectral class is divided into 10 subclasses $A0, A1, A2, ...A9$. The classes and subclasses represent a sequence of temperatures, from hotter (O stars) to cooler (M stars) and from hotter ($A0$) to cooler ($A9$).

Spectral Type	Surface Temperature	Distinguishing Features
O	> 25,000K	H; HeI; HeII
B	10,000-25,000K	H; HeI; HeII absent
A	7,500-10,000K	H; CaII; HeI and HeII absent
F	6,000-7,500K	H; metals (CaII, Fe, etc)
G	5,000-6,000K	H; metals; some molecular species
K	3,500-5,000K	metals; some molecular species
M	< 3,500K	metals; molecular species (TiO!)
C	< 3,500K	metals; molecular species (C2!)

Luminous Classification

Stars are also classified by luminosity class. Luminosity classes are determined from spectral features and photometric measurements, coupled with information regarding the distance to the star and the amount of extinction of the starlight from interstellar material. The luminosity class designation describes the size (gravitational acceleration in the photosphere) of a star from the atmospheric pressure. For larger stars of a given spectral type, the surface gravity decreases relative to what it was on the main sequence, and this decreases the equivalent widths of the absorption lines.

Luminosity Class	Description	Comments
0	Hypergiants	extreme
Ia	Supergiants!	large and luminous
Ib	Supergiants!	less luminous than Ia
II	Bright Giants	
III	Giants	
IV	Sub-Giants	
V	Dwarfs	Main Sequence
sd	Sub-Dwarfs	
D	White Dwarfs	

1.5.2 Life Cycle of Stars

Stars go through a cycle of birth, life, and death. The life cycle of a star depends on its mass. For example, a star like our Sun will live for about 10 billion years, while a star 20 times its mass will only live for a few million years. During a star's life, it fuses hydrogen into helium, releasing energy in the form of light and heat.

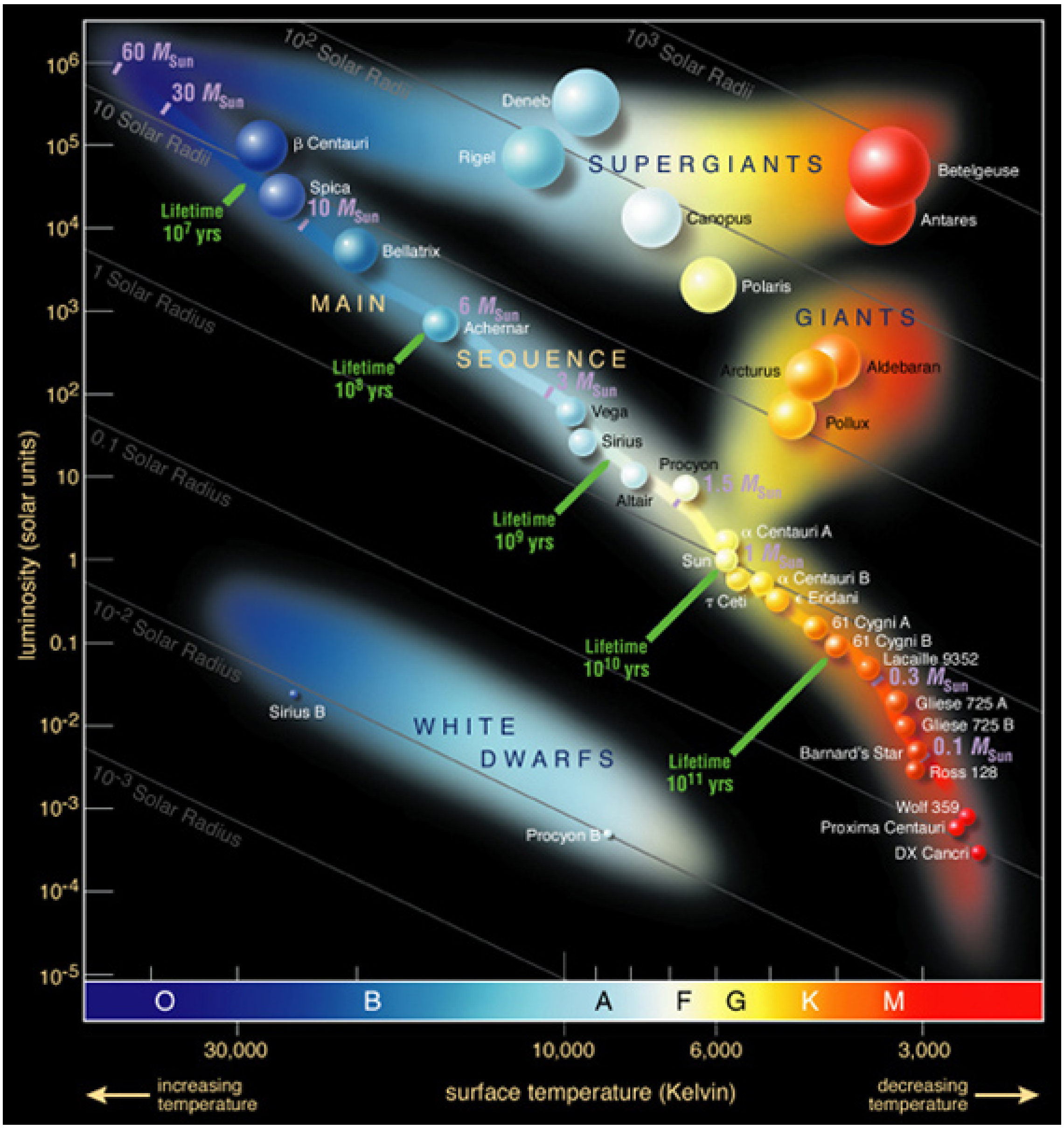
As a star ages and runs out of hydrogen fuel, it may start fusing helium into heavier elements like carbon and oxygen. This causes the star to expand and cool, becoming a red giant. Eventually, the star will shed its outer layers, leaving behind a hot, dense core known as a white dwarf.

If the star is massive enough, it may undergo a violent explosion known as a supernova. During a supernova, the star's core collapses, creating a burst of energy that can briefly outshine an entire galaxy. The explosion also creates heavy elements like gold, silver, and uranium.

Sometimes, the core of a massive star will collapse even further, forming a neutron star. Neutron stars are incredibly dense, with a single teaspoon of neutron star material weighing as much as a mountain. They also have incredibly strong magnetic fields and can spin incredibly fast.

```
+----------------------+  +-----------------------+  +-----------------------+
|  0.8-11 Solar Masses  |  |   11-50 Solar Masses   |  |    >50 Solar Masses    |
+----------------------+  +-----------------------+  +-----------------------+
|   Main sequence star  |  |   Main sequence star   |  |  Main sequence O star  |
|     (B, A, F, or G)   |  |        (O or B)        |  |                        |
|           +-----------+  |           +------------+  |           +------------+
|           |           |  |           |            |  |           |            |
|           v           |  |           v            |  |           v            |
|       Red giant       |  | Red or blue supergiant |  |    Wolf-Rayet Star     |
|      with He core     |  |      with He core      |  |           +------------+
|           +-----------+  |           +------------+  |           |            |
|           |           |  |           |            |  |           v            |
|           v           |  |    Planetary nebula    |  |   Type Ib Supernova    |
|  Red supergiant with  |  |                        |  |           +------------+
|  carbon-oxygen core   |  |           +------------+  |           |            |
|           +-----------+  |           |            |  |           v            |
|           |           |  |           v            |  |       Black Hole       |
|           v           |  |     Red supergiant     |  |                        |
|      White Dwarf      |  |     with iron core     |  |                        |
+----------------------+  +-----------------------+  +-----------------------+
```

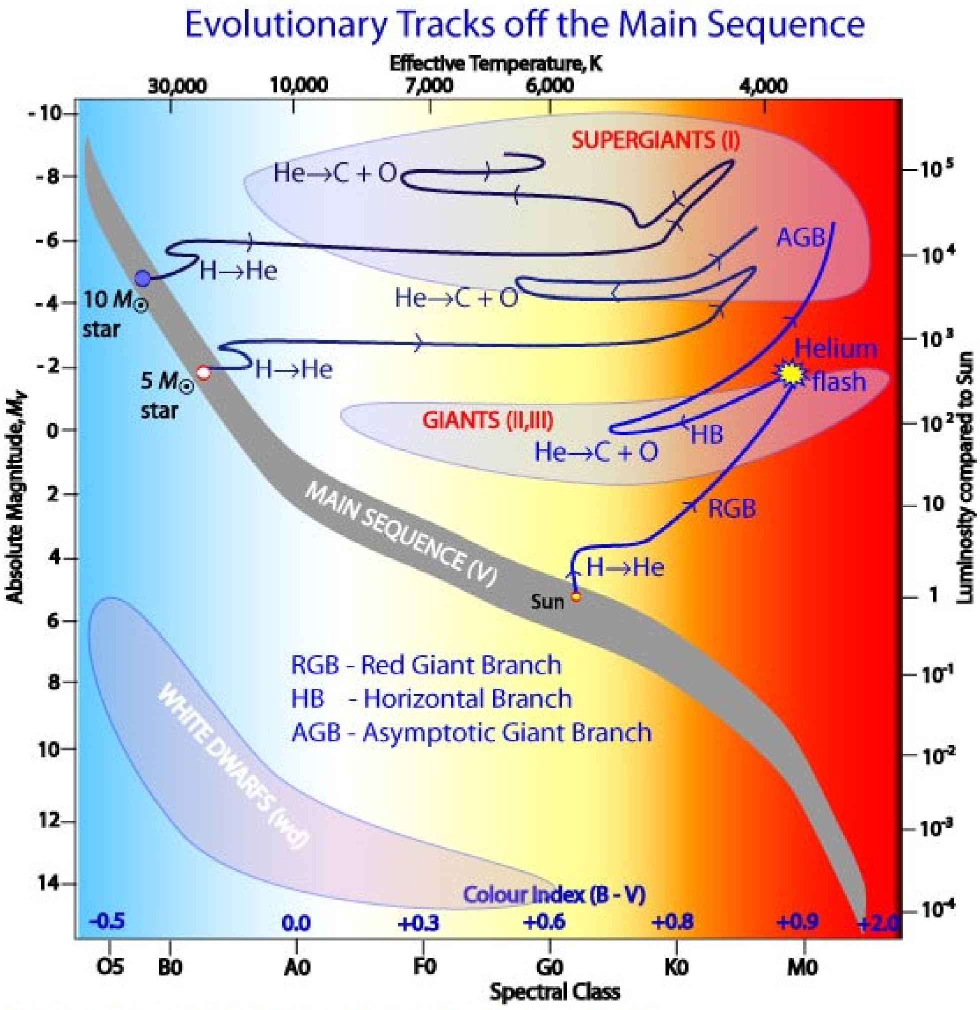
The position of a star on the HR diagram is also dependent on which stage of its life cycle it is in.



Main Sequence Stars

Main sequence stars are stars that fuse hydrogen into helium in their cores. They are the most common type of star in the universe and are classified by their spectral type and luminosity class. Our Sun is a main sequence star of spectral type G2V and luminosity class V.

Low-mass stars stay on the main sequence, with stars with masses less than 0.5 solar masses unable to burn helium.



Post-main sequence evolutionary tracks for 1, 5 and 10 solar mass stars.

Red Giant

A red giant is a dying star in the final stages of stellar evolution. Red giant stars are so named because they are much larger than main sequence stars like our Sun.

A medium-sized star, will eventually burn out of hydrogen and start burning helium. As it expands, it will become cooler and thus drift off the main sequence to the right into the Red Giant Branch (RGB).

As it continues to burn helium in the core, the outer layers burn hydrogen and dump the helium in the core. At one point there is so much helium being burnt in the core that it enters a stage called the helium flash. Due to this, its size decreases and temperature increases, moving the star right on the HR diagram into the Horizontal Branch (HB).

Eventually, it runs out of helium and expands to burn heavier elements, moving along the Asymptotic Giant Branch (AGB).

As a red giant star ages, it will cool down and become less luminous, eventually shedding its outer layers and leaving behind a core known as a white dwarf. Some red giants, however, may undergo a supernova explosion instead, creating heavy elements and releasing enormous amounts of energy.

White Dwarfs

White dwarfs are what is left when stars like our sun have exhausted all of their fuel. They are dense, dim, stellar corpses — the last observable stage of evolution for low- and medium-mass stars. Whilst most massive stars will eventually go supernova, a low or medium-mass star with a mass less than about 8 times the mass of the sun will eventually become a white dwarf. The maximum mass a white dwarf can have is 1.4 solar masses, which is called the Chandrasekhar limit.

These stars are present at the bottom left, as labeled in Figure 1.5.

Neutron Stars

Neutron stars are incredibly dense, with a single teaspoon of neutron star material weighing as much as a mountain. They are formed when the core of a massive star collapses even further than it would to become a white dwarf, creating a super-dense ball of neutrons. Neutron stars also have incredibly strong magnetic fields and can spin incredibly fast.

Black Holes

Black holes are formed when the core of a massive star collapses further than it would to become a neutron star. The gravitational pull at the surface of a black hole is so strong that nothing, not even light, can escape it. Anything that gets too close to a black hole will be sucked in and destroyed. Black holes are still not fully understood and remain one of the most mysterious objects in the universe.

Metallicity of a Star

The metallicity of a star refers to the abundance of elements heavier than helium in its atmosphere. Stars with high metallicity are thought to have formed from the remnants of previous generations of stars, while stars with low metallicity are thought to be some of the oldest stars in the universe. By studying the metallicity of stars, astronomers can learn more about the early universe and the processes that led to the formation of galaxies and stars.

The formula for metallicity is:

$$(\mathrm{Fe/H}) = \log_{10}\left(\frac{\mathrm{Fe}}{\mathrm{H}}\right) - \log_{10}\left(\frac{\mathrm{Fe}}{\mathrm{H}}\right)_{\odot}$$

where Fe is the abundance of iron and H is the abundance of hydrogen. The solar value for Fe/H is used as a reference point. (Fe/H) is often used as a measure of metallicity because iron is one of the most abundant heavy elements in the universe. By studying the metallicity of stars, astronomers can learn more about the early universe and the processes that led to the formation of galaxies and stars.

2. The Study of Open Clusters

2.1 Introduction

There are two main types of star clusters: Open Clusters and Globular clusters. An open cluster refers to a specific type of star cluster composed of tens to a few thousand stars while globular cluster is a group ten thousands to millions of old stars that are bounded very strongly by gravitational forces. Open clusters originate from a common giant molecular cloud and have almost the same age. The Milky Way galaxy alone has yielded the discovery of over 1,100 open clusters, with scientists speculating the existence of many more. These clusters are held together by a loose gravitational attraction among their members but are prone to disruption when they encounter other clusters or gas clouds during their orbits around the Galactic Center.

Open clusters originate from the collapse of giant molecular clouds, which are dense accumulations of gas and dust. These clouds, with masses several thousand times that of the Sun, maintain equilibrium through magnetic fields, turbulence, and rotation. Various factors can disrupt this equilibrium, such as shock waves from supernovae, cloud collisions, or gravitational interactions. The collapse of a molecular cloud triggers star formation within regions of higher density (quantitatively in regions where density is 10^4 hydrogen molecules per cm^3). The cloud fragments hierarchically into smaller clumps, eventually giving rise to several thousand stars. During this process, protostars remain obscured within the collapsing cloud, visible only in infrared light. The most massive and hottest stars among the newly formed cluster emit intense ultraviolet radiation, ionizing the surrounding gas and creating an H II region. Stellar winds and radiation pressure from these stars disperse the ionized gas at the speed of sound. Over millions of years, the cluster may experience core-collapse supernovae, expelling additional gas from the vicinity. This gas expulsion, combined with other processes, limits the cluster's lifespan to approximately ten million years, halting further star formation. Gas expulsion has significant effects on open clusters. Only a fraction of the original gas content forms stars, resulting in infant weight loss and significant mortality rates. For example, when Pleiades was formed only one-third of stars remained and the rest became unbounded. The formation of an open cluster depends on the gravitational binding of its stars; otherwise, an unbound stellar association may form. The remaining stars contribute to the Galactic field population.

The following open clusters were selected to be analysed:

1. M44 Beehive Cluster
2. M6 Butterfly Cluster
3. NGC 2264 Christmas Tree Cluster
4. M67 King Cobra Cluster
5. M34
6. M35
7. M25
8. M23

2.2 Selecting Cluster Members

We considered the top 10,000 brightest stars in the Gaia EDR3 catalog. A common criterion is to choose those that exhibit a good Gaussian fit for distance and possess a prominent peak above the background. This approach ensures that the selected clusters have a well-defined central tendency and distinct characteristics that distinguish them from the surrounding data points. We used the list of open clusters on Wikipedia that have a distance range of less than 2000 pc, as Gaia data on parallax worsens as we increase distance. To make the data better, there was filtering done on the basis of clustering in the pmra/pmdec space as well. Error cuts on pmra and pmdec were not used as they severely reduced the number of stars we got from a query. The selection criteria were:

- Parallax is not NULL
- Error in Parallax < 20
- Order by G band magnitude in descending order

2.2.1 ADQL Query

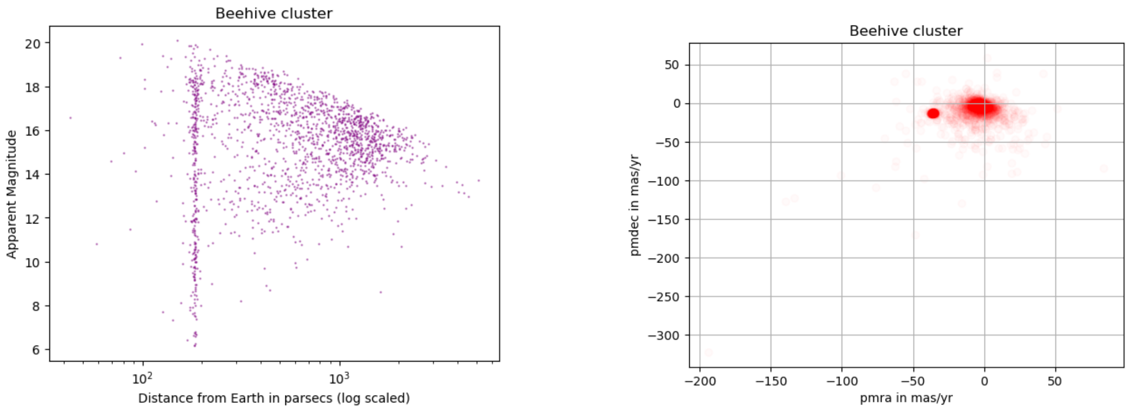
An example of an ADQL query is as follows

```
query = '''SELECT top 10000 source_id, ra, dec, parallax, phot_g_mean_mag,
phot_bp_mean_mag, phot_rp_mean_mag, pm, pmra, pmdec
from gaiadr3.gaia_source
where ra between 83.32 and 84.32
AND dec between -5.89 and -4.89
AND parallax_over_error > 10
AND parallax is not NULL
order by phot_g_mean_mag DESC'''
```

Following is a procedure followed used for all clusters to be analyzed. A few examples have been taken to illustrate the procedure.

2.2.2 Beehive cluster

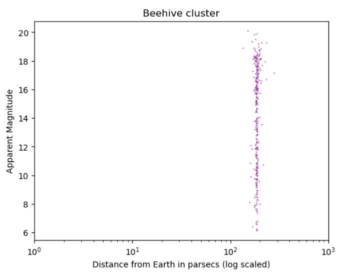
This is the most ideal scenario; for all star clusters, one may not get such a good result. On querying, we checked for any apparent clustering based on a scatter plot between apparent magnitude and logarithmically scaled distance from Earth, and then we check for clumping in the pmra/pmdec space.

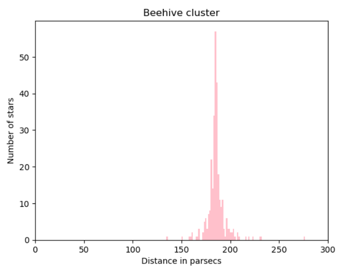


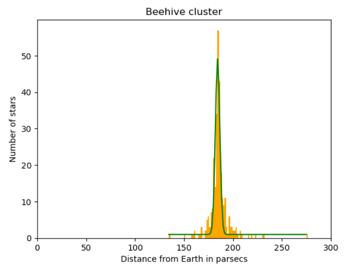
(a) Plot of distance and apparent mag (b) Plot of pmra and pmdec

Figure 2.1: From plot we can infer that the cluster is at some distance larger than 100 parsecs, while the other plot has two clumps; one slightly dense one of background stars at (0,0) and the other very dense one at (-40, -10) which is the cluster

We query again, this time with pmra and pmdec filters. After that, we find the histogram of the distance of stars from Earth and fit a Gaussian distribution to find the mean and standard deviation. We take the clusters position to be at the mean, and member stars to be within 3 times the standard deviation around the mean.







(a) Plot of distance and apparent magnitude, after filtering pmra/pmdec.

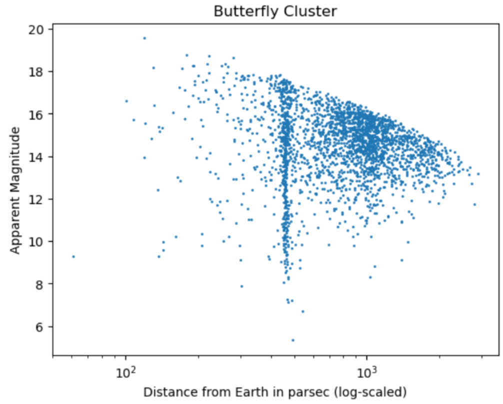
(b) Histogram of distance after pmra/pmdec filtering

(c) Histogram of distance, with a Gaussian curve fitting.

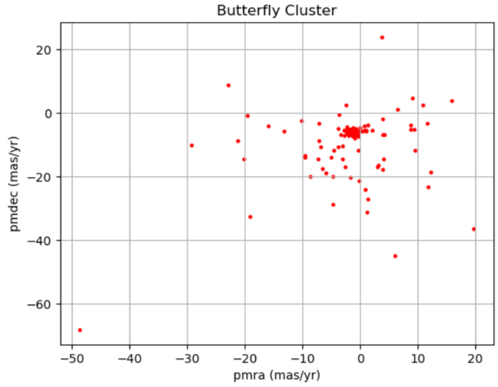
In this manner, we are able to get the cluster members.

2.2.3 Butterfly Cluster

M6 is a superb bright naked eye open cluster in the constellation of Scorpius that's also known as the Butterfly Cluster. M6 is located in eastern Scorpius. Its RA and DEC coordinates are 17h 40m 6s and -32° 13′ 0", respectively. After querying for particular region and giving 0.2 parallax over error, we found a cluster in pmra/pmdec space.



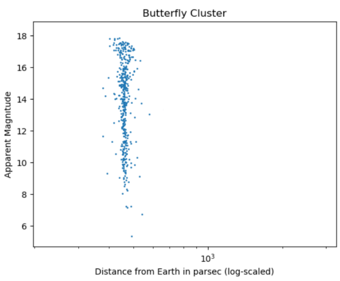
(a) Plot of distance and apparent mag



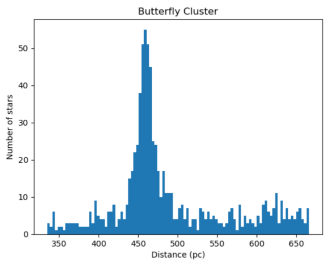
(b) Plot of pmra and pmdec

Figure 2.3: From plot we can infer that the cluster is at nearly half a 1000 parsecs, while the other plot in pmra-pmdec space shows a clump which is the cluster

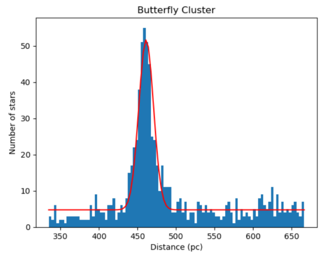
Now we query for pmra and pmdec filters. We then plot a histogram of number of stars in the cluster with respect to their distance from Earth and fit a Gaussian distribution to find the mean and standard deviation. We take the clusters position to be at the mean, and member stars to be within 3 times the standard deviation around the mean.



(a) Plot of distance and apparent magnitude, after filtering pmra/pmdec.



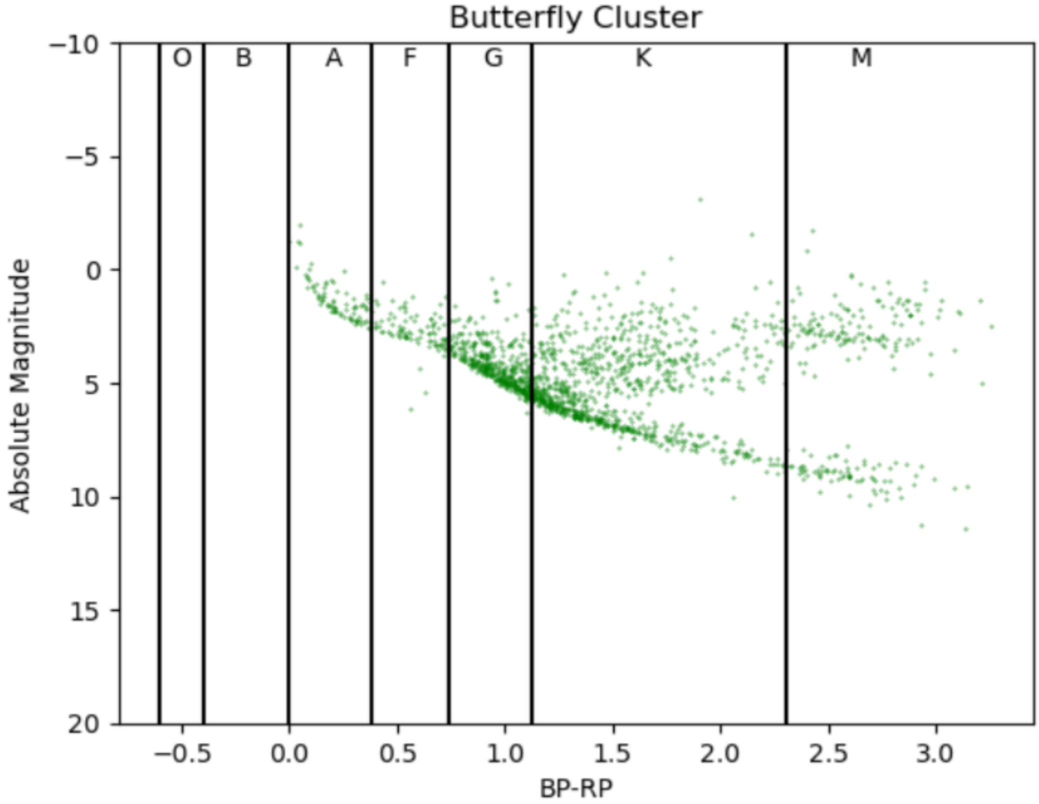
(b) Histogram of distance for pmra/pmdec filtering.



(c) Histogram of distance, with a Gaussian curve fitting.

Figure 2.4: After filtering to stars other than the cluster, we plotted the histogram to find at what distance the maximum number of stars situated from Earth. Then after fitting gaussian curve, we found the mean = 461.29pc, standard deviation = 9.6pc

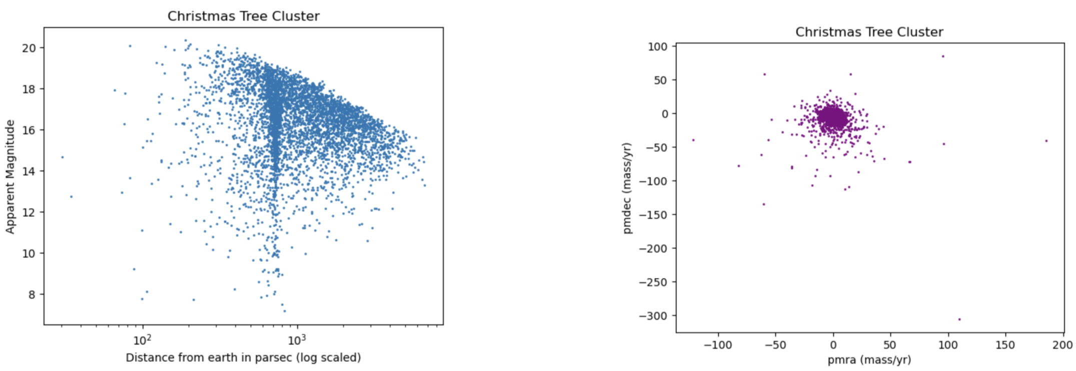
After masking for the particular values of pmra and pmdec, we calculated the bprp values by subtracting rp mean magnitude from bp mean magnitude, and then plot absolute magnitude against these bprp values.



We get the fraction of O B A F G K M stars for Butterfly cluster as follows:
O : 0, B : 0, A : 4.98, F : 5.35, G : 26.03, K : 50.65, M : 12.69

2.2.4 Christmas Tree Cluster

The Christmas Tree Cluster, also known as NGC 2264, is a stunning open cluster located in the constellation of Monoceros. Resembling a Christmas tree during the holiday season, this cluster is a favorite among skywatchers in the northern hemisphere. Its celestial coordinates are 06h 40m 58s right ascension and 09° 53′ 43" declination. After querying for particular region and giving 5 parallax over error, we found a cluster in pmra/pmdec space.

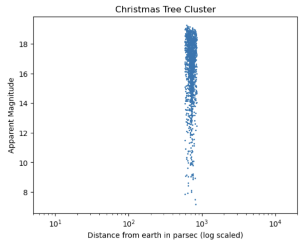


(a) Plot of distance and apparent mag

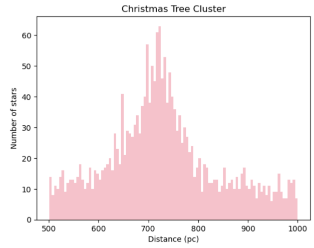
(b) Plot of pmra and pmdec

Figure 2.5: From plot we can infer that the cluster is at nearly 700 parsecs, while the other plot in pmra-pmdec space shows a clump which is the cluster

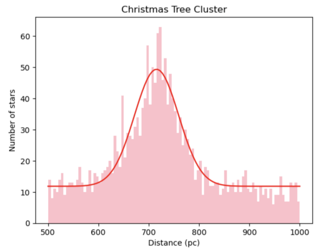
Now we query for pmra and pmdec filters. We then plot a histogram of number of stars in the cluster with respect to their distance from Earth and fit a Gaussian distribution to find the mean and standard deviation. We take the clusters position to be at the mean, and member stars to be within 3 times the standard deviation around the mean.



(a) Plot of distance and apparent magnitude, after filtering pmra/pmdec.



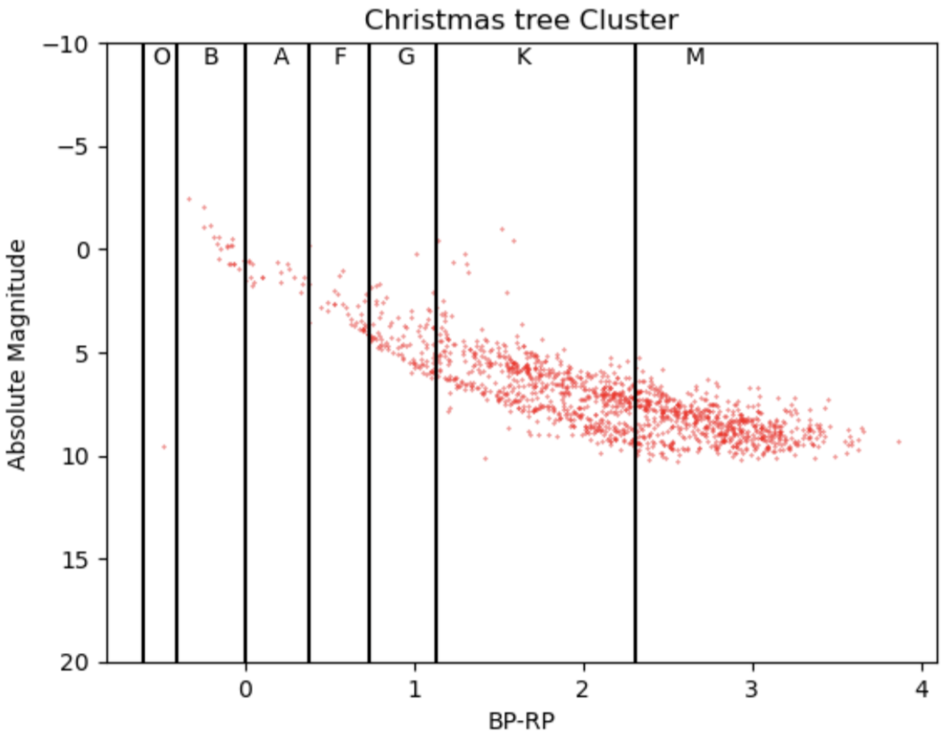
(b) Histogram of distance for pmra/pmdec filtering.



(c) Histogram of distance, with a Gaussian curve fitting.

Figure 2.6: After filtering to stars other than the cluster, we plotted the histogram to find at what distance the maximum number of stars situated from Earth. Then after fitting gaussian curve, we found the mean = 715.56pc, standard deviation = 43.85pc

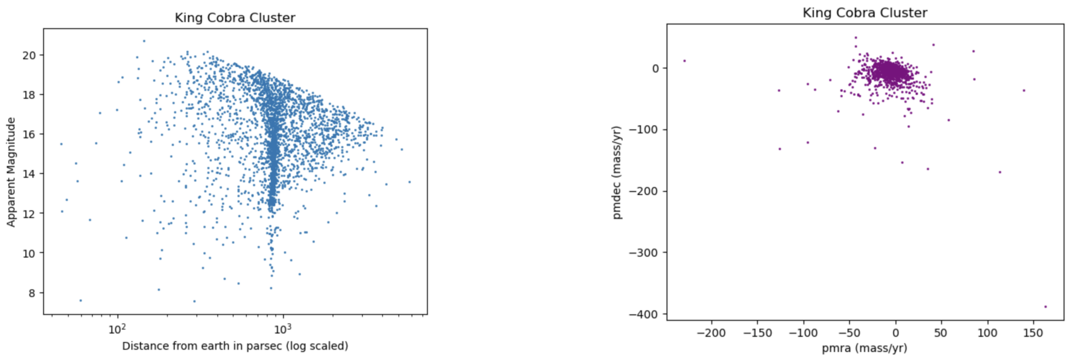
After masking for the particular values of pmra and pmdec, we calculated the bprp values by subtracting rp mean magnitude from bp mean magnitude, and then plot absolute magnitude against these bprp values.



We get the fraction of O B A F G K M stars for Butterfly cluster as follows:
O : 0.07, B : 1.41, A : 1.41, F : 2.32, G : 6.55, K : 43.94, M : 42.32

2.2.5 King Cobra Cluster

The King Cobra Cluster, also recognized as Messier 67 (M67) cluster, stands as a remarkable open cluster situated in the constellation of Cancer. This cluster, known for its stellar beauty and intricate arrangement of stars, holds a special place among astronomers and stargazers worldwide. The celestial coordinates pinpoint its location at approximately 08h 51m 20s right ascension and 11° 48′ 42" declination. After querying for particular region and giving 5 parallax over error, we found a cluster in pmra/pmdec space.

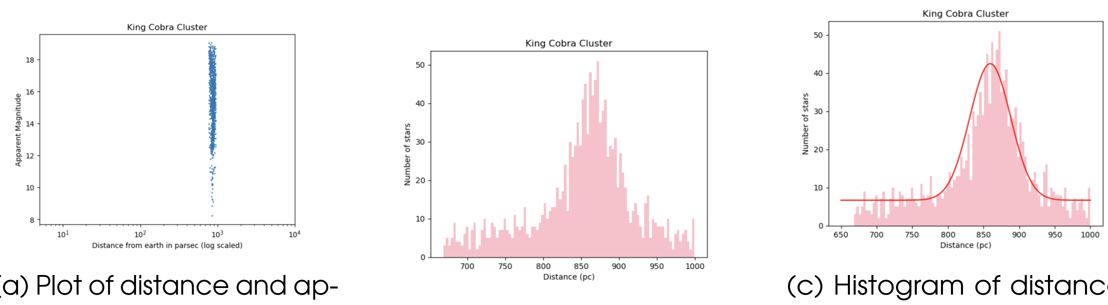


(a) Plot of distance and apparent mag

(b) Plot of pmra and pmdec

Figure 2.7: From plot we can infer that the cluster is at nearly 800 parsecs, while the other plot in pmra-pmdec space shows a clump which is the cluster

Now we query for pmra and pmdec filters. We then plot a histogram of number of stars in the cluster with respect to their distance from Earth and fit a Gaussian distribution to find the mean and standard deviation. We take the clusters position to be at the mean, and member stars to be within 3 times the standard deviation around the mean.



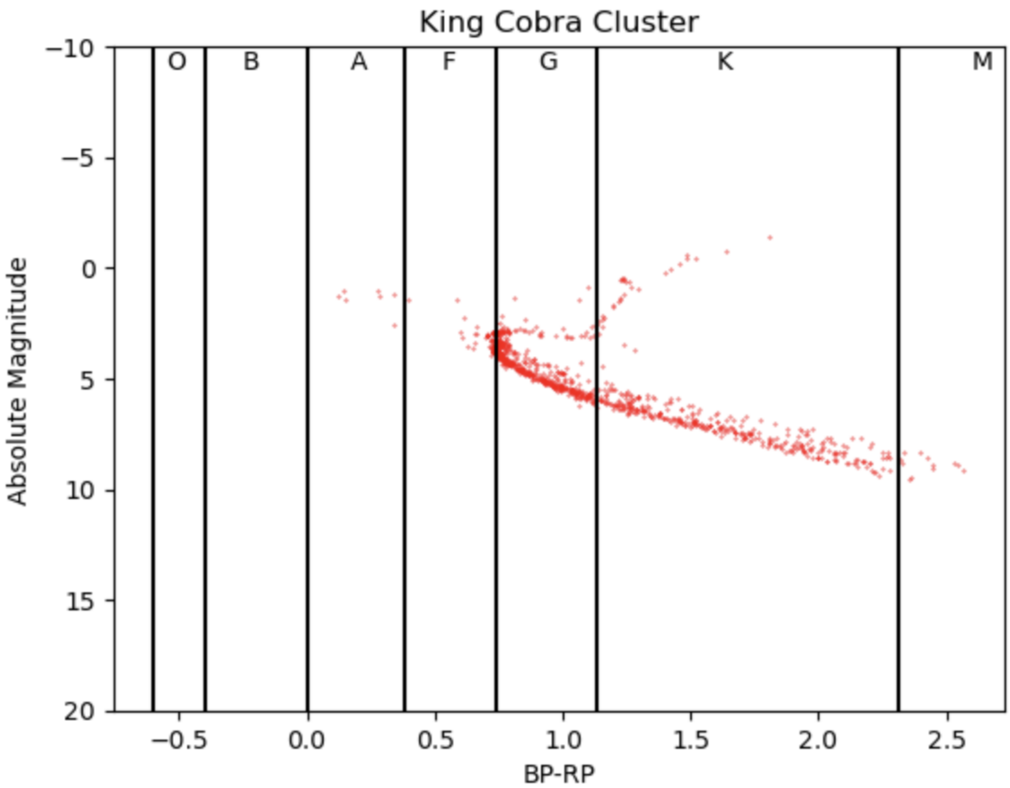
(a) Plot of distance and apparent magnitude, after filtering pmra/pmdec.

(b) Histogram of distance for pmra/pmdec filtering.

(c) Histogram of distance, with a Gaussian curve fitting.

Figure 2.8: After filtering to stars other than the cluster, we plotted the histogram to find at what distance the maximum number of stars situated from Earth. Then after fitting gaussian curve, we found the mean = 859.41pc, standard deviation = 28.71pc

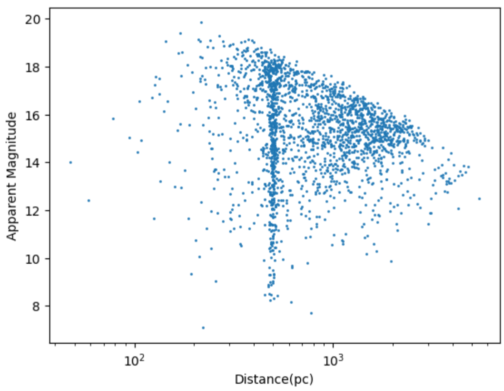
After masking for the particular values of pmra and pmdec, we calculated the bprp values by subtracting rp mean magnitude from bp mean magnitude, and then plot absolute magnitude against these bprp values.



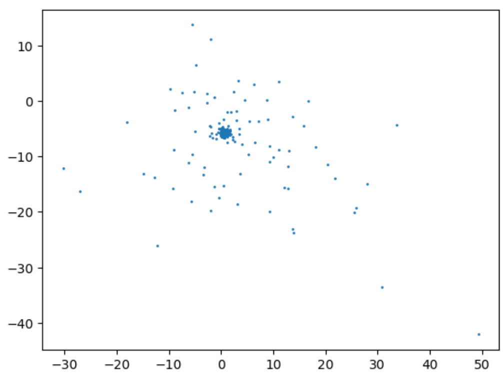
We get the fraction of O B A F G K M stars for Butterfly cluster as follows:
O : 0, B : 0, A : 0.74, F : 8.91, G : 49.42, K : 39.66, M : 1.27

2.2.6 M34

Messier 34 (also known as M34 or NGC 1039) is a large and relatively near open cluster in the constellation of Perseus. Its RA and DEC coordinates are 02h 42m 6s and 42° 46′ 0", respectively. After querying for particular region and giving 10 parallax over error, we found a cluster in pmra/pmdec space.



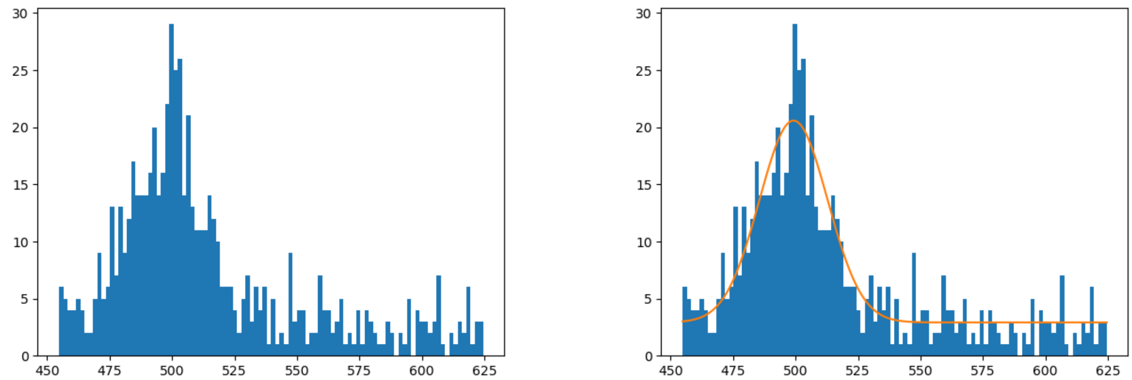
(a) Plot of distance and apparent mag



(b) Plot of pmra and pmdec

Figure 2.9: From plot we can infer that the cluster is at nearly half a 500 parsecs, while the other plot in pmra-pmdec space shows a clump which is the cluster

Now we query for pmra and pmdec filters. We then plot a histogram of number of stars in the cluster with respect to their distance from Earth and fit a Gaussian distribution to find the mean and standard deviation. We take the clusters position to be at the mean, and member stars to be within 3 times the standard deviation around the mean.

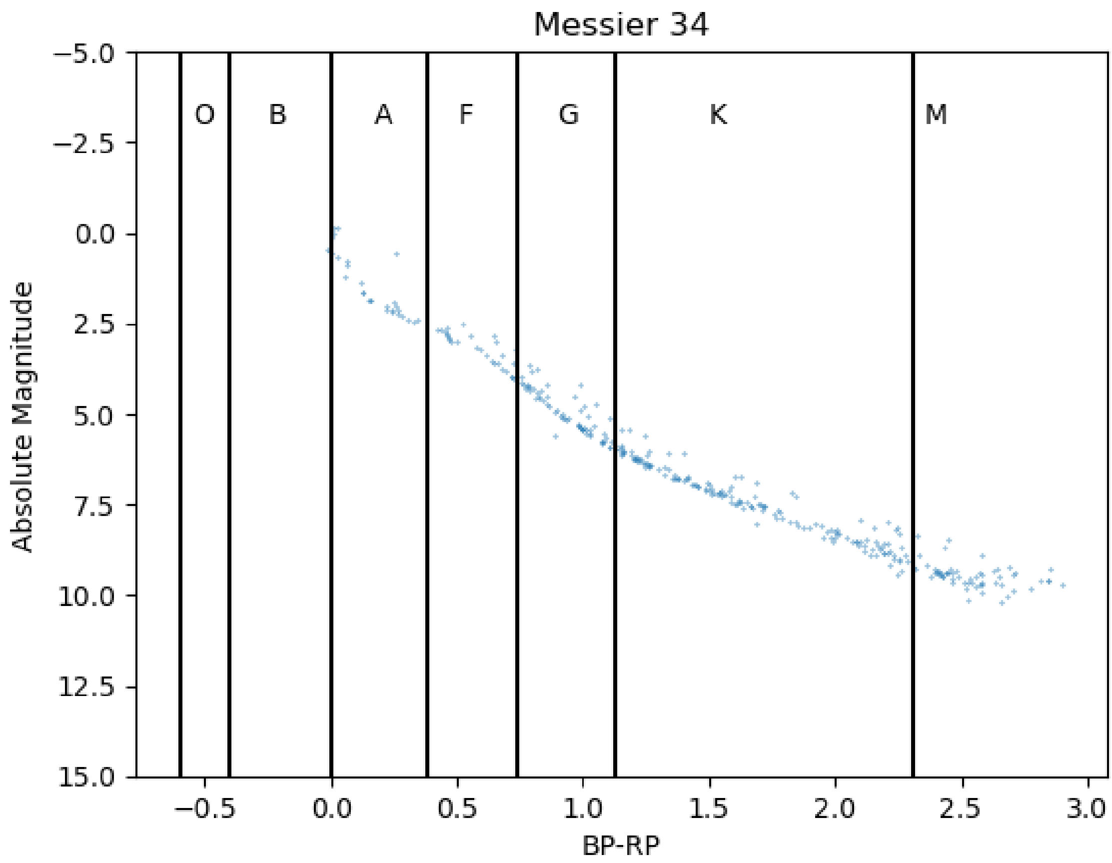


(a) Histogram of distance for pmra/pmdec filtering.

(b) Histogram of distance, with a Gaussian curve fitting.

Figure 2.10: After filtering to stars other than the cluster, we plotted the histogram to find at what distance the maximum number of stars situated from Earth. Then after fitting gaussian curve, we found the mean = 499.18pc, standard deviation = 2.92pc

After masking for the particular values of pmra and pmdec, we calculated the bprp values by subtracting rp mean magnitude from bp mean magnitude, and then plot absolute magnitude against these bprp values.

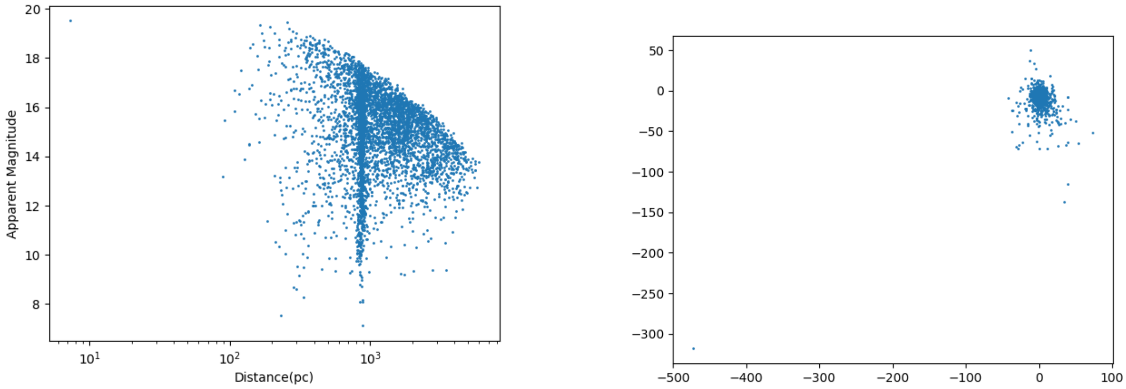


We get the fraction of O B A F G K M stars for M34 as follows:

O : 0, B : 1.19 A : 7.74, F : 8.33, G : 19.05, K : 46.43, M : 17.26

2.2.7 M35

Messier 35 or M35, also known as NGC 2168, is a relatively close open cluster of stars in the west of the constellation Gemini, at about the declination of the sun when the latter is at June solstice. Its RA and DEC coordinates are 06h 09m 6s and 24° 21′ 0", respectively. After querying for particular region and giving 10 parallax over error, we found a cluster in pmra/pmdec space.

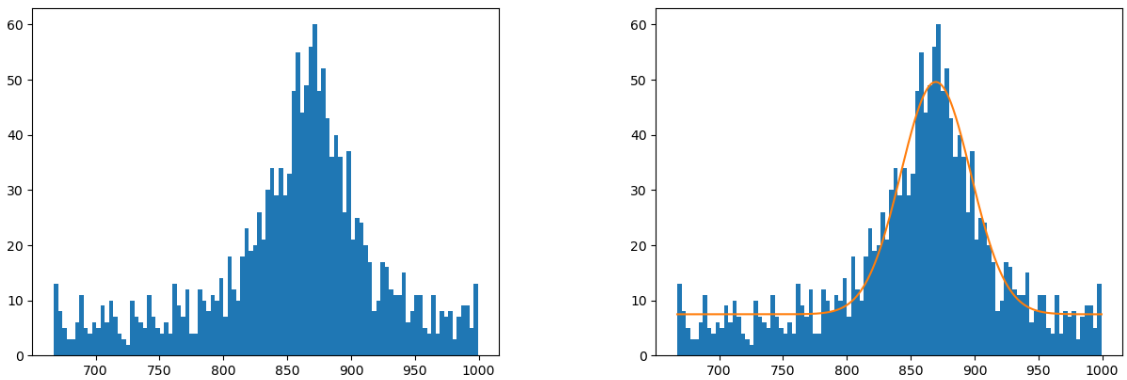


(a) Plot of distance and apparent mag

(b) Plot of pmra and pmdec

Figure 2.11: From plot we can infer that the cluster is at nearly half a 900 parsecs, while the other plot in pmra-pmdec space shows a clump which is the cluster

Now we query for pmra and pmdec filters. We then plot a histogram of number of stars in the cluster with respect to their distance from Earth and fit a Gaussian distribution to find the mean and standard deviation. We take the clusters position to be at the mean, and member stars to be within 3 times the standard deviation around the mean.

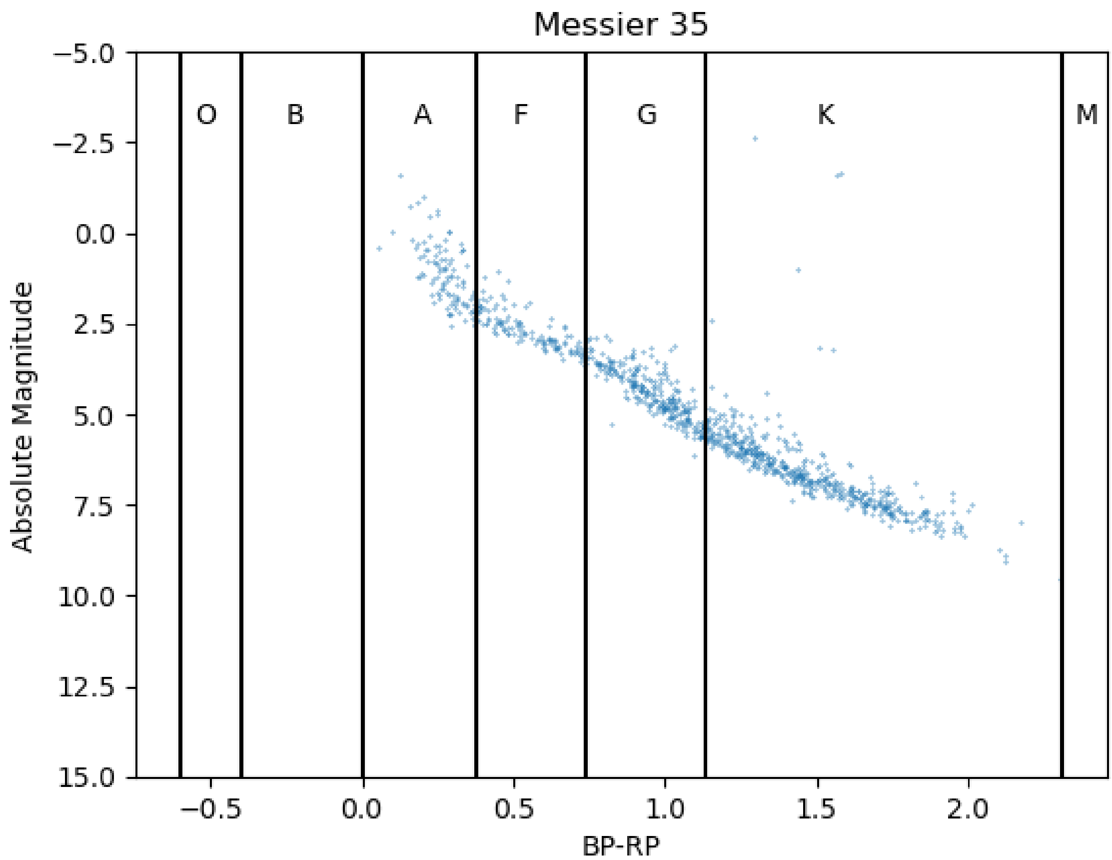


(a) Histogram of distance for pmra/pmdec filtering.

(b) Histogram of distance, with a Gaussian curve fitting.

Figure 2.12: After filtering to stars other than the cluster, we plotted the histogram to find at what distance the maximum number of stars situated from Earth. Then after fitting gaussian curve, we found the mean = 869.62pc, standard deviation = 7.47pc

After masking for the particular values of pmra and pmdec, we calculated the bprp values by subtracting rp mean magnitude from bp mean magnitude, and then plot absolute magnitude against these bprp values.



We get the fraction of O B A F G K M stars for M34 as follows:

O : 0, B : 0 A : 11.01, F : 12.26, G : 27.04, K : 49.37, M : 0

2.2.8 M25

Messier 25, also known as IC 4725, is an open cluster of stars in the southern constellation of Sagittarius. It's RA and DEC coordinates are 18h 31m 47s and -19° 04′ 00", respectively. After querying for a square region of 1° angular width and height centered around it's RA and DEC coordinates, we found the following:

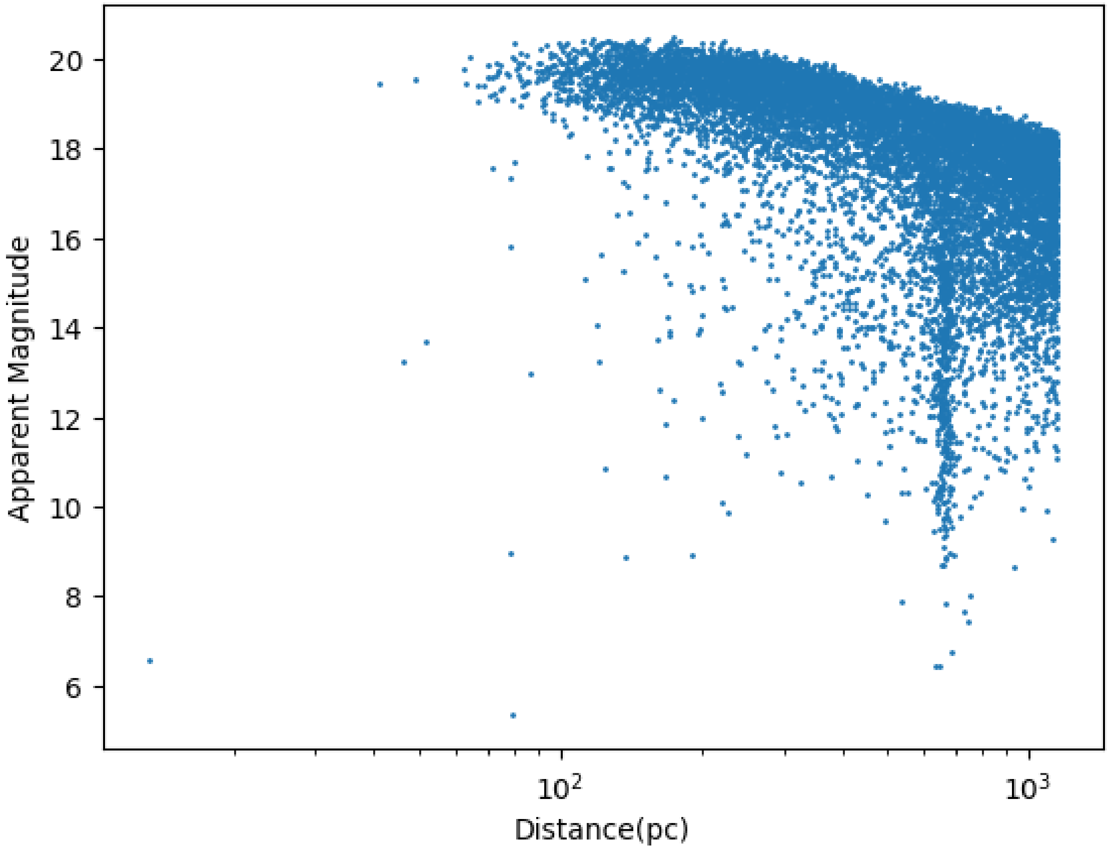
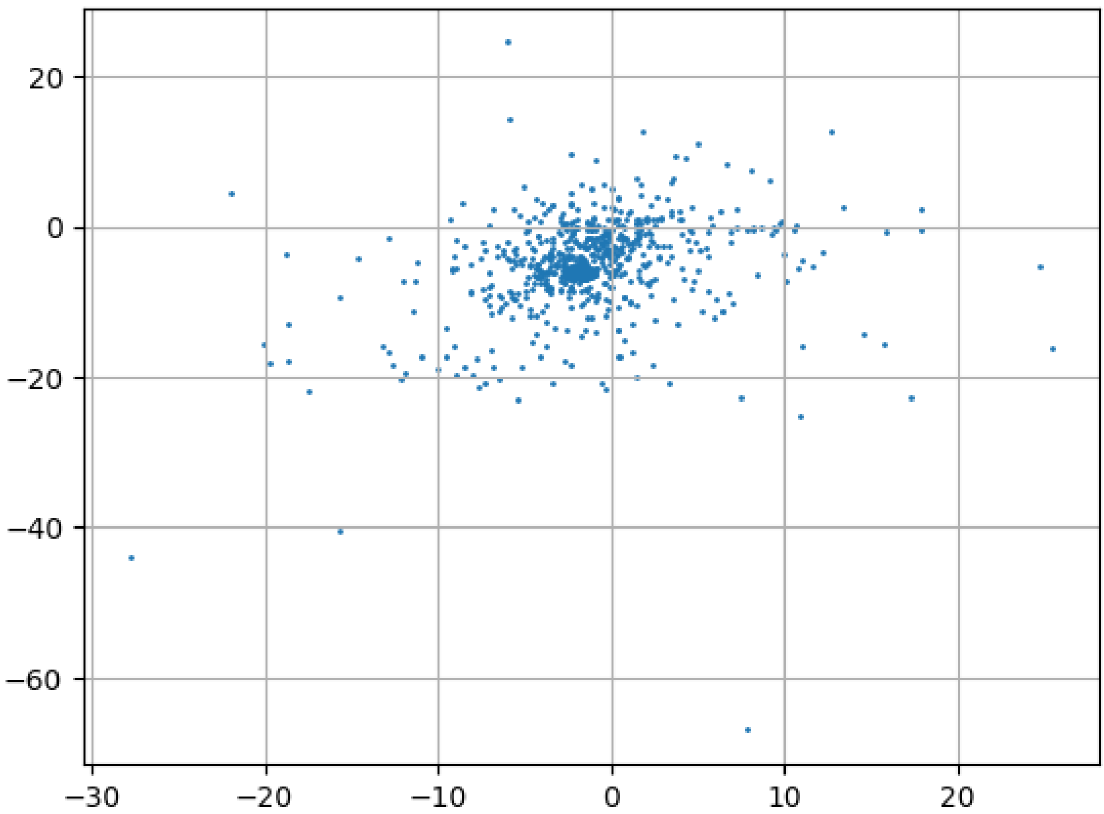


Figure 2.13: From plot we can infer that the cluster is at nearly half a distance of 660 parsecs

Now we plot a histogram of number of stars in the cluster with respect to their distance from Earth and fit a Gaussian distribution to find the mean and standard deviation. We take the clusters position to be at the mean, and member stars to be within 3 times the standard deviation around the mean.
We obtain this clustering in the pmra-pmdec space.



After masking for the particular values of pmra and pmdec, we calculated the bp-rp values by subtracting rp mean magnitude from bp mean magnitude, and then plot absolute magnitude against these bprp values.

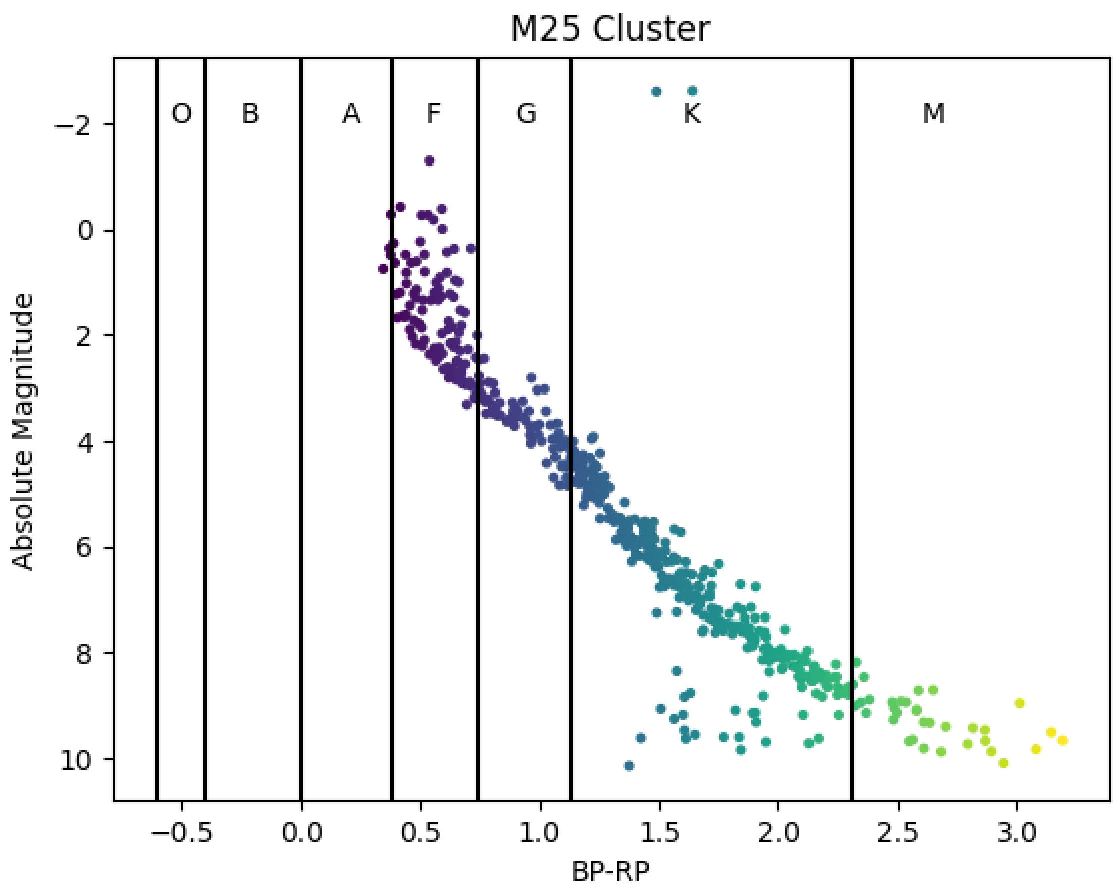


Figure 2.14: Plot of absolute magnitude vs temperature

We get the fraction of O B A F G K M stars for M25 as follows:
O : 0, B : 0, A : 0.73, F : 18.46, G : 13.71, K : 58.87, M : 6.40

2.2.9 M23

Messier 23, also known as NGC 6494, is an open cluster of stars in the northwest of the southern constellation of Sagittarius. The cluster is centered about 2,050 light years away. The cluster is around 330 million years old with a near-solar metallicity of (Fe/H) = -0.04.
It's RA and DEC coordinates are 17h 15m 04s and -18°59'06", respectively. We query for a square region of 1° angular width centered around these coordinates and a ration of parallax/error > 5.

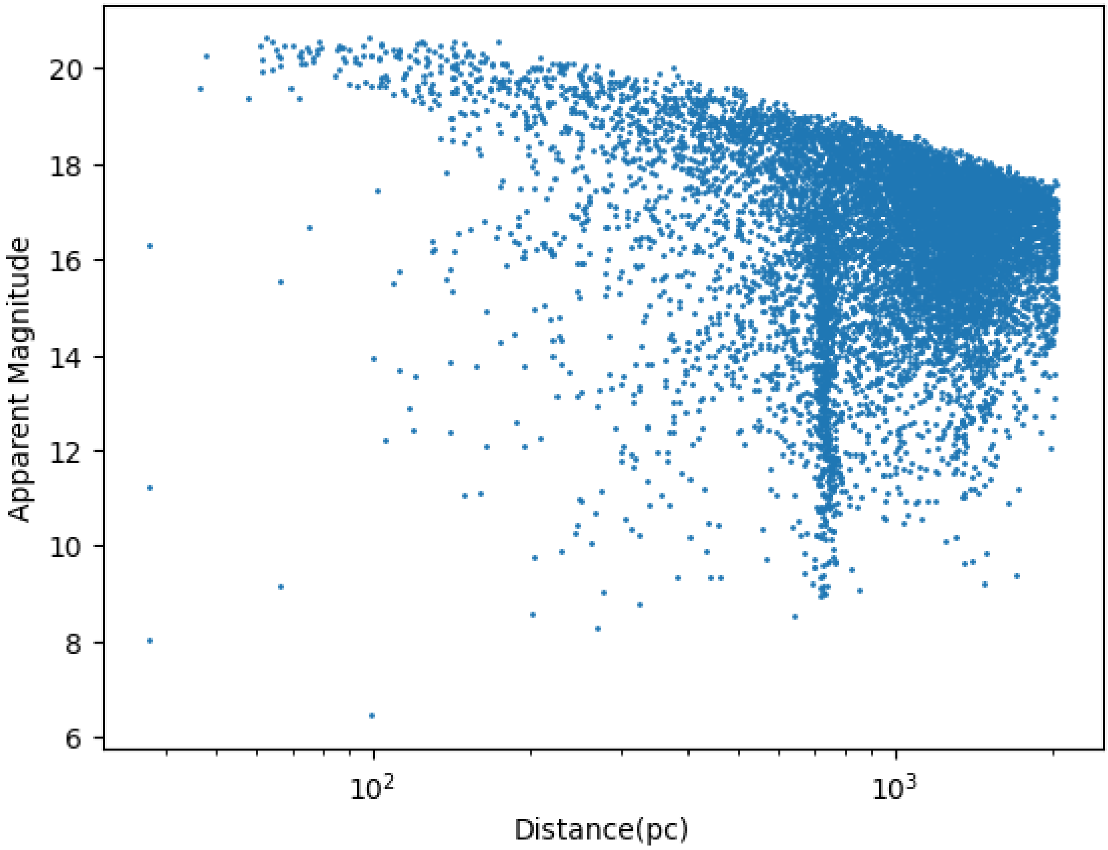


Figure 2.15: Plot of distance vs apparent magnitude for the stars obtained from our query. We can infer that the cluster is around 700 - 800 parsecs from Earth

We plot the proper motion of these stars and find clustering in the pmra-pmdec space.

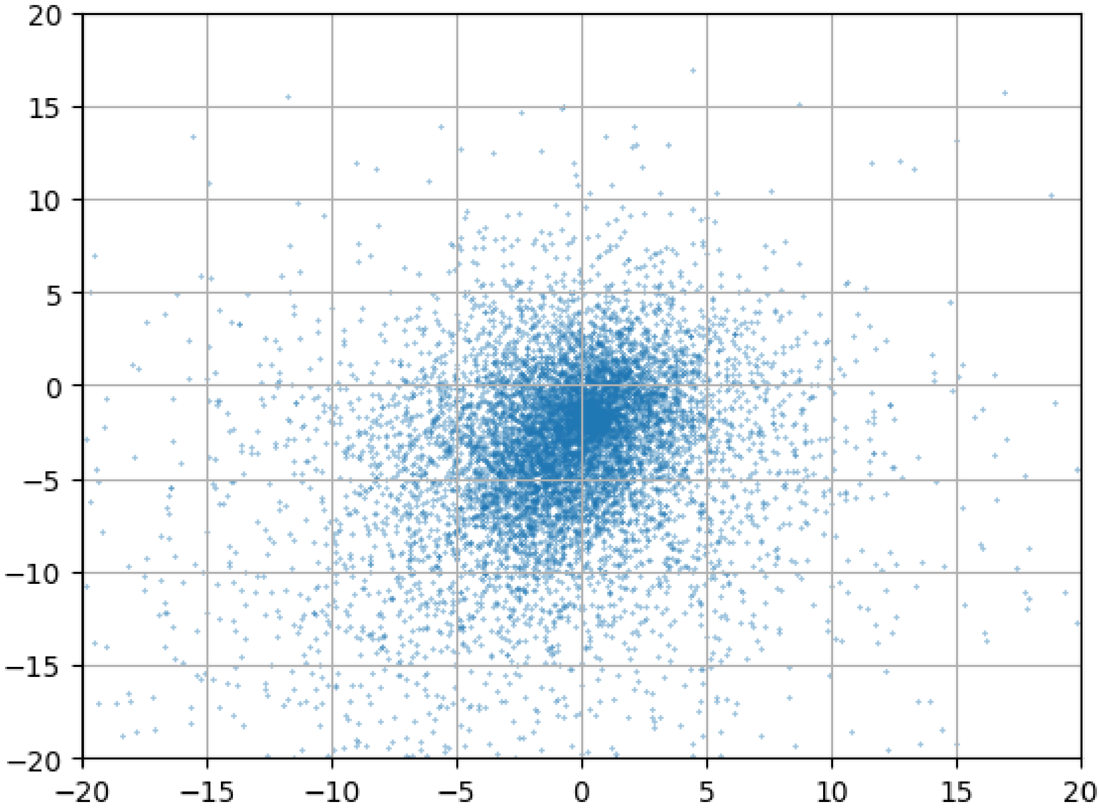
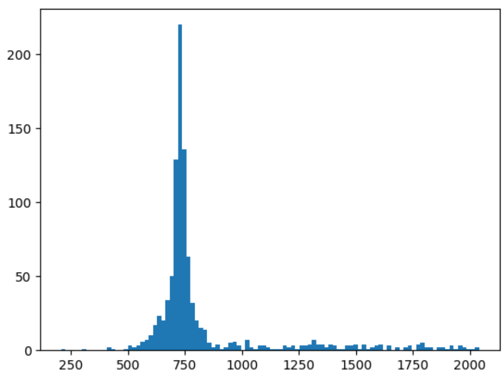
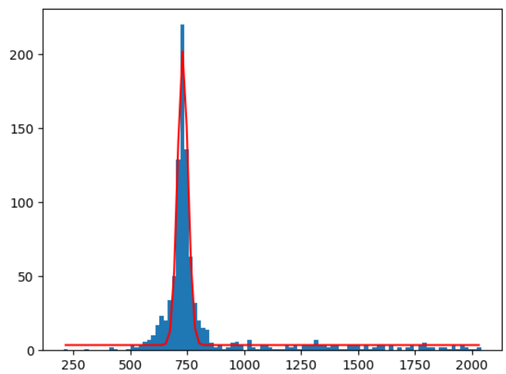


Figure 2.16: Plot of pmra-pmdec (with limits on x and y axes to be able to find the clustering). We can use this to identify the cluster as all stars in a cluster have the same proper motion through space.

Now we plot a histogram of the distance and fit a Gaussian curve to it. Then we take stars that are within 3 sigma of the mean.



(a) Histogram of distance after pmra/pmdec filtering.



(b) Histogram of distance, with a Gaussian curve fitting.

Now we we calculate the bp-rp values by subtracting rp mean magnitude from bp mean magnitude, and then plot absolute magnitude against these bprp values.

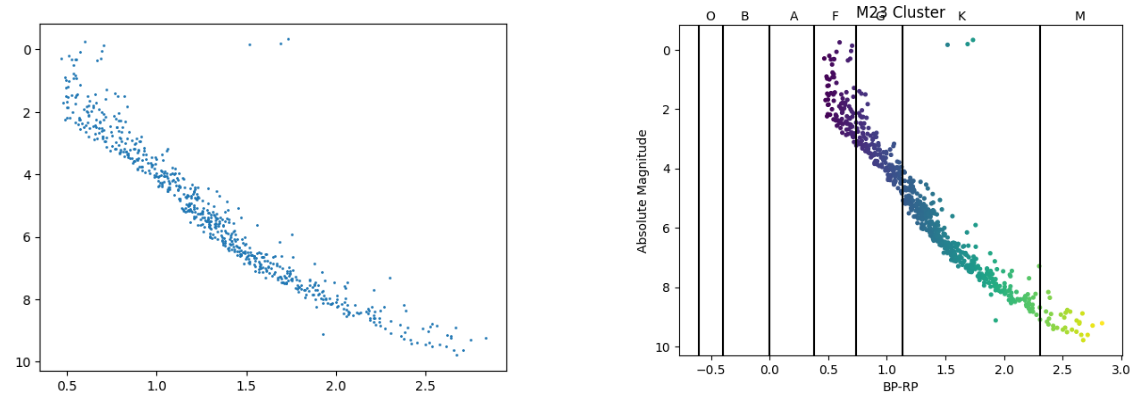
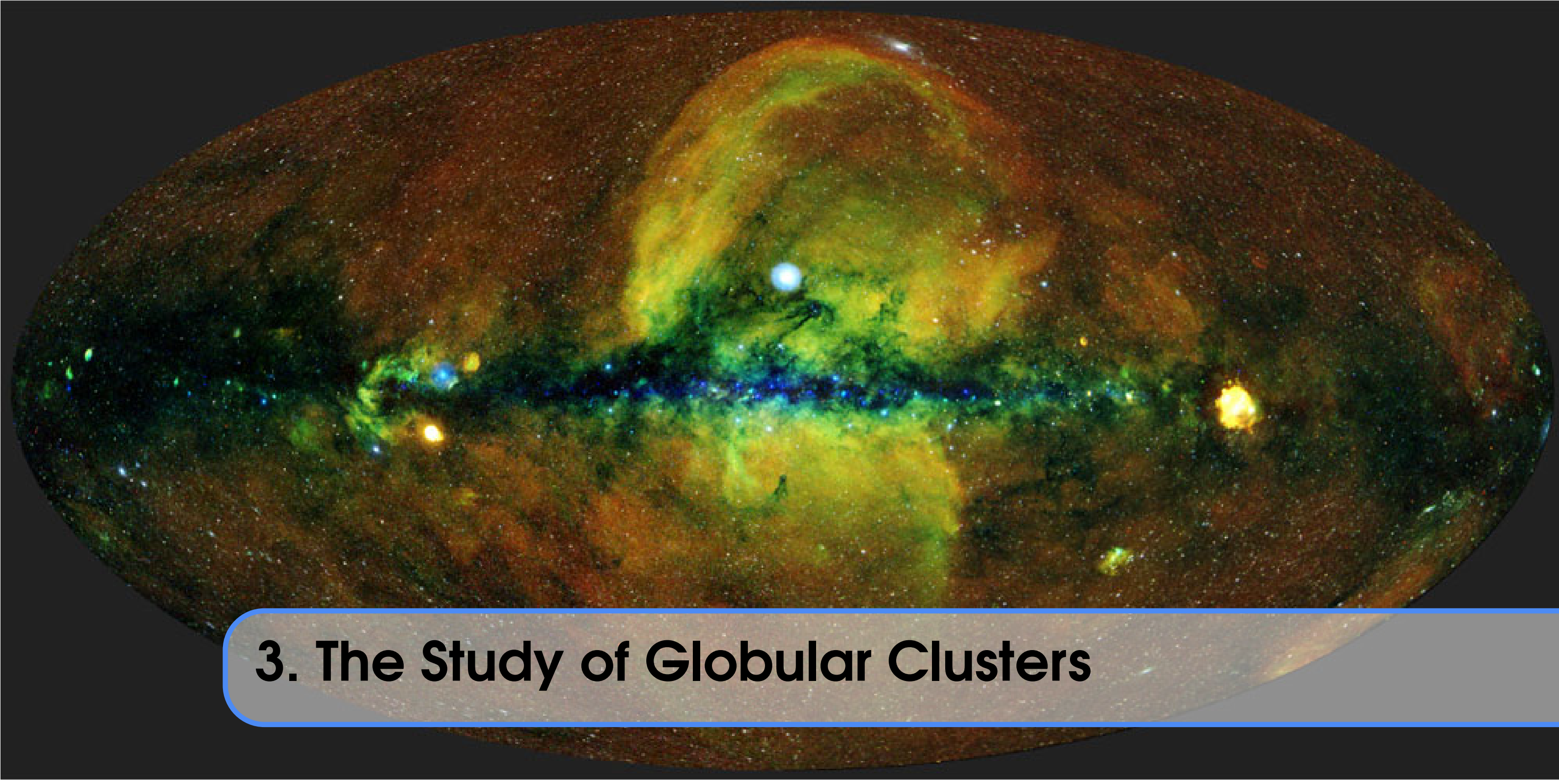


Figure 2.18: Plots of absolute magnitude vs temperature

We get the fraction of O B A F G K M stars for M23 as follows:
O : 0
B : 0
A : 0
F : 14.01
G : 21.76
K : 59.02
M : 4.32



3. The Study of Globular Clusters

3.1 Introduction

There are two main types of star clusters: Open Clusters and Globular clusters. We saw about open clusters in the last chapter.

All globular clusters are roughly spherical (which accounts for their name). Globular clusters are found in nearly all galaxies. In spiral galaxies like the Milky Way they are mostly found in the outer spheroidal part of the galaxy – the galactic halo. They are the largest and most massive type of star cluster, tending to be older, denser, and composed of lower abundances of heavy elements than open clusters, which are generally found in the disks of spiral galaxies. The most outstanding feature of globular clusters is their lack of upper main-sequence stars. In fact, globular clusters contain no main-sequence stars with masses greater than about 0.8 times the mass of the Sun. (The A-type stars are stars at a much later evolutionary stage that happen to be passing through the location of the upper main sequence). Their more massive O- through F-type stars have long since exhausted their nuclear fuel and disappeared from the main sequence. On the basis of these and other observations, astronomers estimate that all globular clusters are at least 10 billion years old. They contain the oldest known stars in our Galaxy. Astronomers speculate that the 150 or so globular clusters observed today are just the survivors of a much larger population of clusters that formed long ago.

3.2 Selecting Cluster Members

We considered all the stars in this case in the 3rd data release catalogue of GAIA. We choose those stars that exhibit a good Gaussian fit for distance and possess a prominent peak above the background, which in turn ensures the well defined central tendency and also the distinctive nature from surrounding data points. As we know that globular clusters are much farther from us in comparison with open clusters, so we will take that distance from infinitely large to some very big distance.

There will be no other quality cuts on parallax, pmra, pmdec. One different thing here will be the Renormalised Unit Weight Error (RUWE). The RUWE is expected to be around 1.0 for sources where the single-star model provides a good fit to the astrometric observations. A value significantly greater than 1.0 (say, >1.4) could indicate that the source is non-single or otherwise problematic for the astrometric solution.The selection criteria will be:

- PMRA is not NULL
- PMDEC is not NULL
- PARALLAX between 0 and 0.25
- RUWE < 1.4

3.2.1 ADQL Query

An example of an ADQL query is as follows

```
query = '''SELECT source_id, ra, dec, parallax, phot_g_mean_mag,
phot_bp_mean_mag, phot_rp_mean_mag, pm, pmra, pmdec
FROM gaiadr3.gaia_source
WHERE
ra between 205.04 and 206.04
and dec between 27.87 and 28.87
and pmra is not NULL
and pmdec is not NULL
and parallax between 0 and 0.25
and ruwe < 1.4'''
```

By following this procedure, we will analyze some examples of globular clusters, and then will find their metallicity and age using Isochrones.

3.3 Isochrones

In stellar evolution, an isochrone is a curve on the Hertzsprung-Russell diagram, representing a population of stars of the same age but with different mass. Isochrones can be used to date clusters because their members all have roughly the same age.

3.4 Examples to Analyze

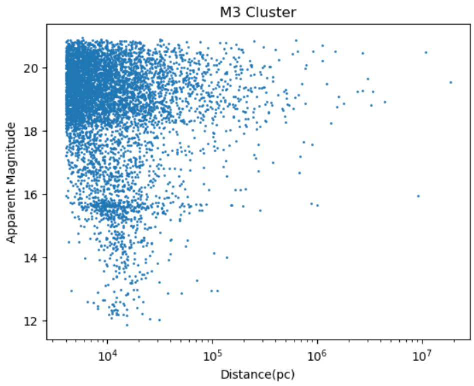
The following globular clusters were selected to be analysed:

1. M3 / NGC 5272 cluster
2. Omega Centauri cluster

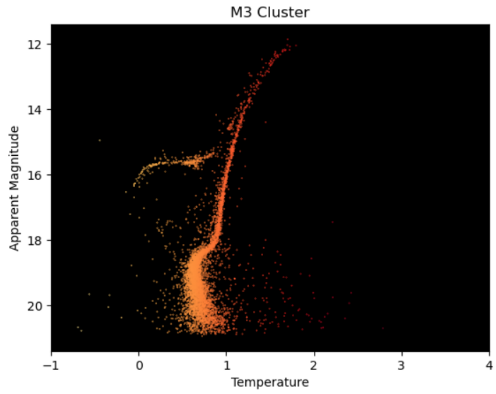
3.4.1 M3 Cluster

Messier 3 (M3; also NGC 5272) is a globular cluster of stars in the northern constellation of Canes Venatici. This cluster is one of the largest and brightest, and is made up of around 500,000 stars. It is estimated to be 11.4 billion years old. It is centered at 32,600 light-years (10.0 kpc) away from Earth. We will try to find out both these things along with its metallicity while analyzing the data. Its RA and

DEC coordinates are 13h 42m 11.62s and 28° 22′ 38.2", respectively. We queried for non-zero pmra/pmdec with giving 0.2 parallax over error and RUWE < 1.4.



(a) Plot of distance and apparent mag

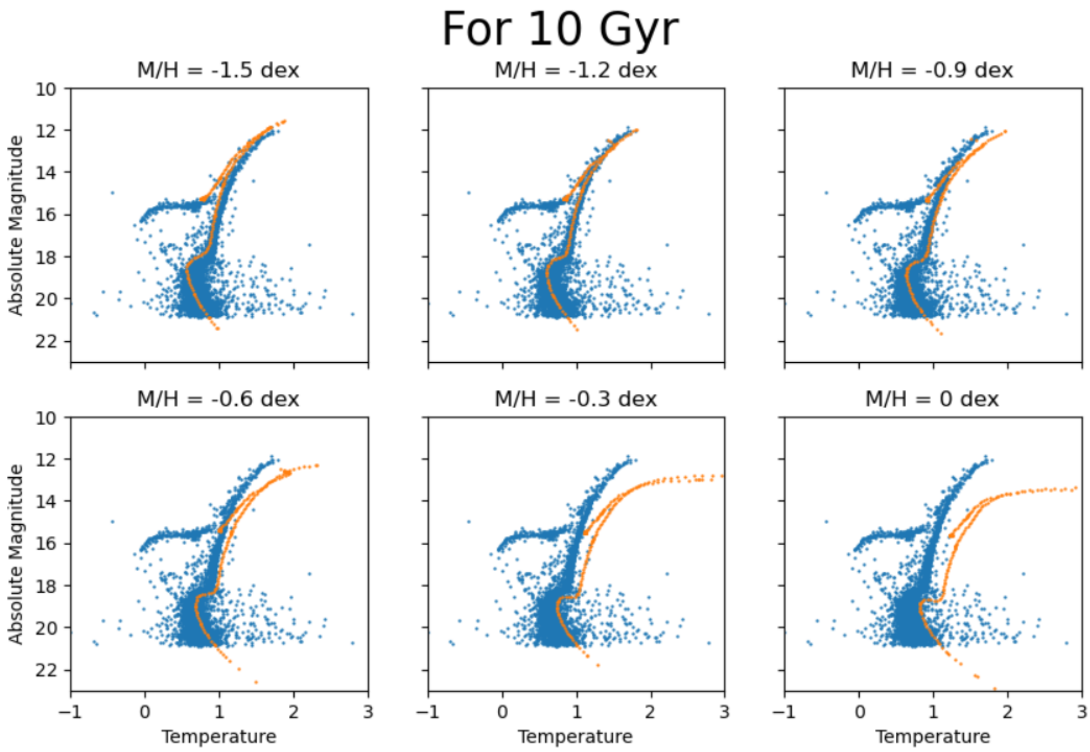


(b) HR diagram of M3 cluster

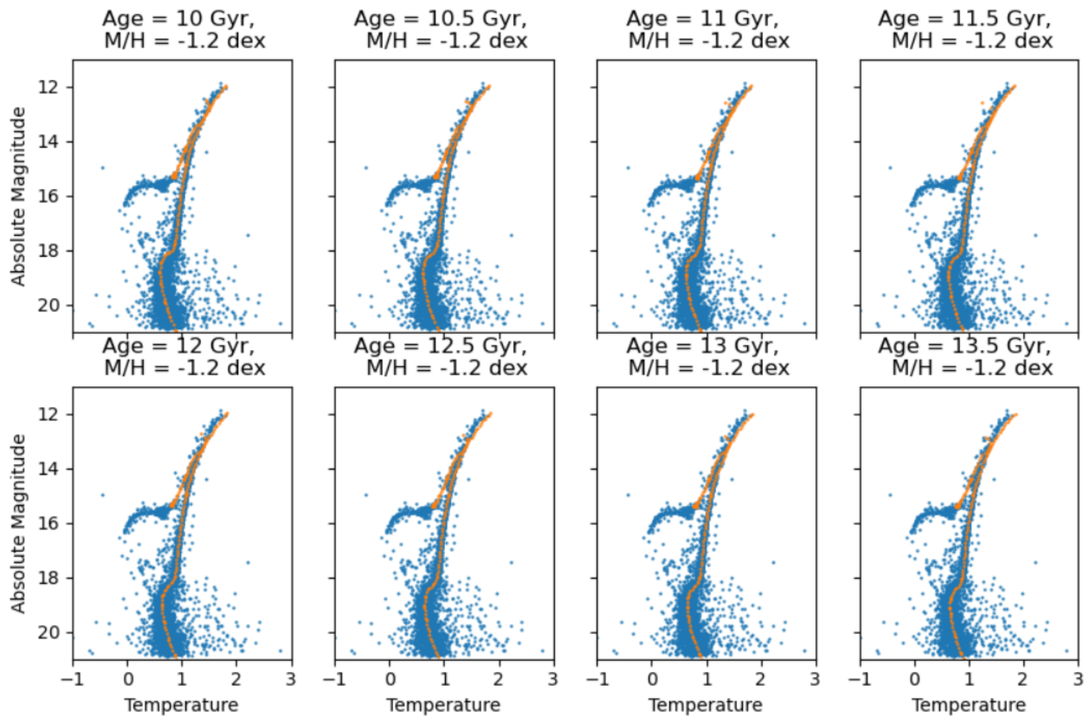
Figure 3.1: In first plot, we can see that there is no cluster. Also in HR diagram, we can see that the stars are upto 20 magnitude only, because GAIA can only measure the objects having magnitude down to 20.

As we know that they are aged of tens of billions of years, so to find age of the cluster, we took range of 10 to 13.5 billion years and take a step of half a billion years. For metallicity, we took range of 0 to -1.5 dex with a step of 0.3 dex. So due to this, we would have a total of 48 isochrones, 6 for each age group. From all 8 age groups, we found 8 isochrones that best fitted with the HR diagram. Further, from these 8 best isochrones, we finally found the "BESTEST" one.

Here, we have shown you plot corresponding to 10 billion years age. But similar plots came for each age.



After plotting for all 8 age groups, we found that isochrone corresponding to -1.2 dex metallicity is the best one for every age. Now we plot the 8 best graphs, and compared visually that which isochrone fitted perfectly among the 'bests'.



After carefully seeing all 8 graphs, isochrone with age 11.5 Gyr fitted very accurately with the HR diagram at turn-off points, Red Giant branch and Red clumps.

So, from this we found metallicity and age of the cluster. Now we have to find its distance from the Earth. For this we used magnitude and distance relation :

$$m - M = 5\log_{10}(\frac{dist}{10})$$

where, *dist* = distance of that object from Earth in parsec.

By taking *dist* in one side, we came to the formula :

$$dist = 10 * 10^{\frac{m-M}{5}}$$

To make the isochrones overlap on HR diagram, we added 15 in absolute magnitude. So *m* - *M* = 15. So,

$$dist = 10 * 10^{15/5} = 10,000pc = 10kpc$$

which very correctly corresponds to the actual value.

3.4.2 Omega Centauri Cluster

Omega Centauri is a globular cluster in the constellation of Centaurus. It is the largest-known globular cluster in the Milky Way at a diameter of roughly 150 light-years. It's RA and DEC coordinates are 13h 26m 47.28s and -47° 28′ 46.1", respectively. It is estimated to be around 11.52 billion years old. We will try to

estimate it's age and metallicity by finding which isochrone best matches it's HR diagram. Also we can estimate the distance to this cluster by the difference between apparent and absolute magnitude.
We find the stars in the cluster by looking for clustering in the pmra/pmdec space. First we visually identify the pmra and pmdec limits then take values within $\pm 3\sigma$ of the mean.

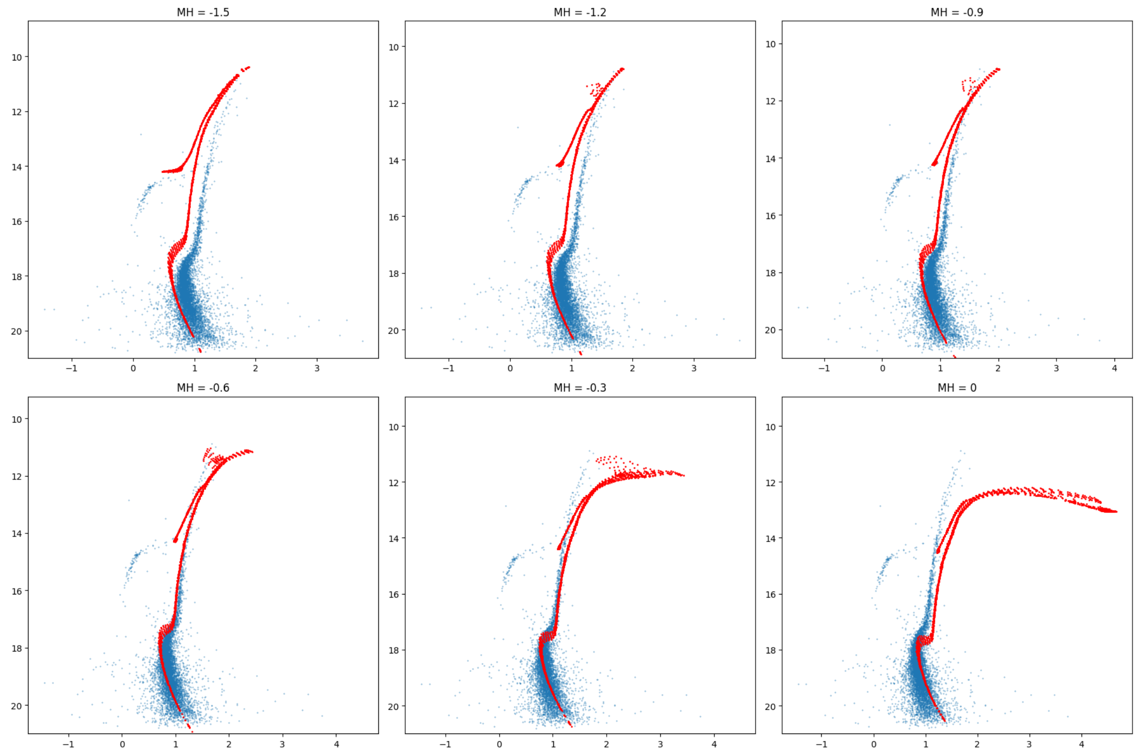


Figure 3.2: Isochrones of metallicities from -1.5 dex to 0 with a step of 0.3 dex

We find that the isochrone corresponding to metallicity = -0.6 dex best matches the HR diagram.

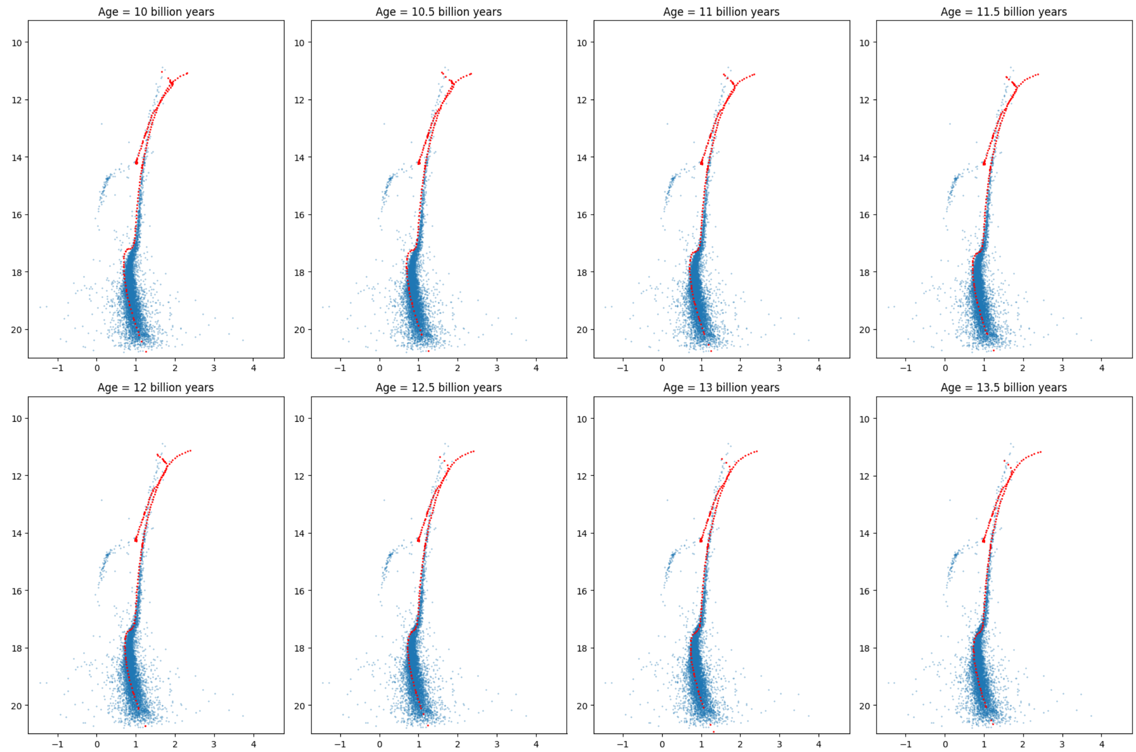


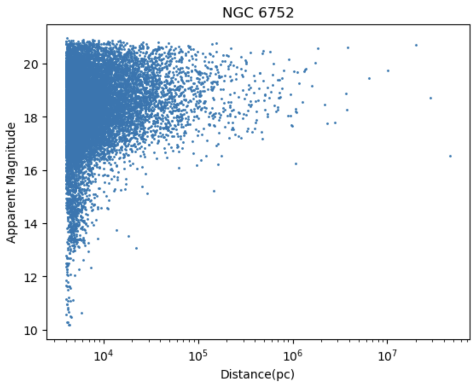
Figure 3.3: Isochrones of age from 10 billion years to 13.5 billion years with a step of 0.5 billion years and metallicity = -0.6 dex

We find that the isochrone corresponding to age = 12 billion years best matches the HR diagram.
The difference between apparent and absolute magnitudes is 13.8. Distance in paresecs is

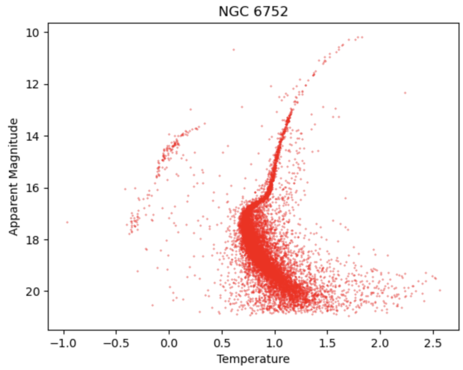
$$10^{(13.8+5)/5} = 5754.4pc$$

3.4.3 NGC 6752 Cluster

Nicknamed the "Great Peacock Globular" or "Caldwell 93", NGC 6752 is situated in the southern constellation of Pavo. This cluster, recognized as one of the brightest and most prominent globular clusters visible from the southern hemisphere, is composed of approximately 100,000 stars. Estimated to be around 11.78 billion years old, NGC 6752 stands as one of the oldest clusters in the Milky Way. Positioned at a distance of approximately 13,000 light-years (4.0 kpc) away from Earth, it holds a significant place in our understanding of stellar evolution and galactic structures. Its precise coordinates are Right Ascension (RA) 19h 10m 52s and Declination (DEC) -59° 59′ 04", defining its location in the night sky. Now, let's embark on a journey into the depths of this mesmerizing globular cluster. We queried for non-zero pmra/pmdec with giving 0.25 parallax over error and RUWE < 1.4.



(a) Plot of distance and apparent mag

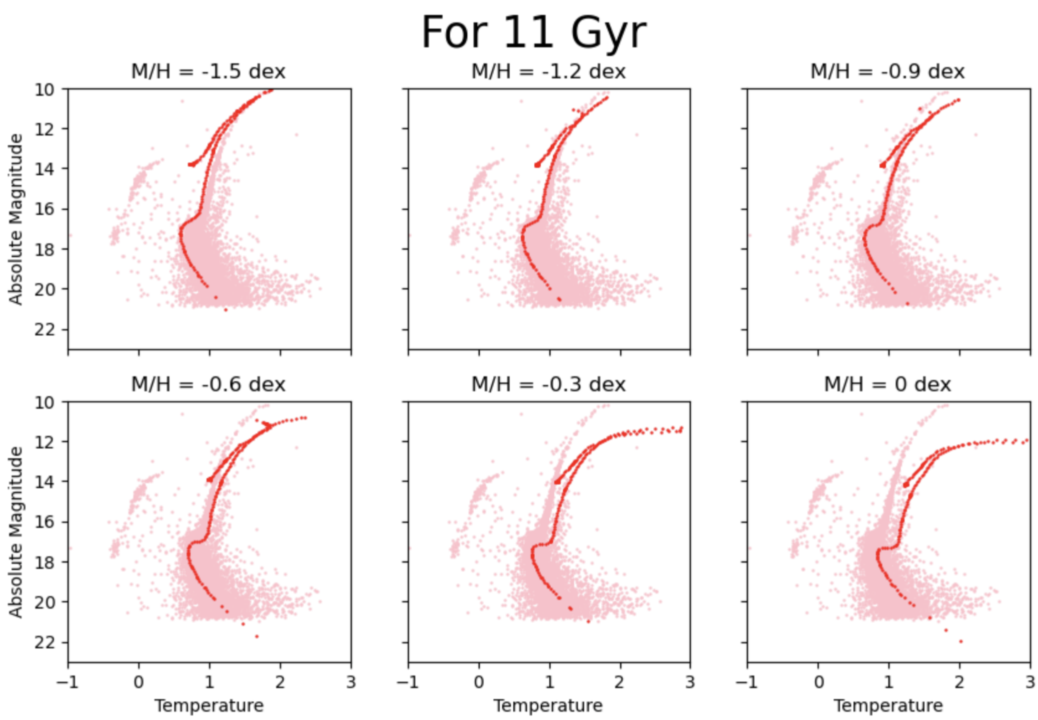


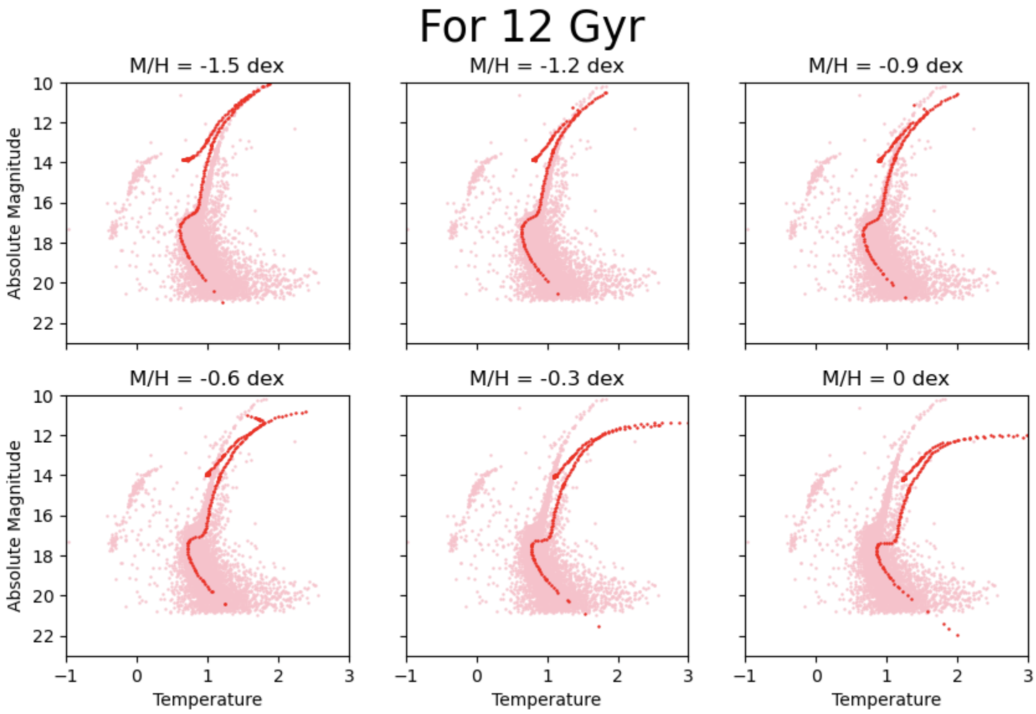
(b) HR diagram of NGC 6752 cluster

Figure 3.4: In first plot, we can see that again there is no cluster which is expected.

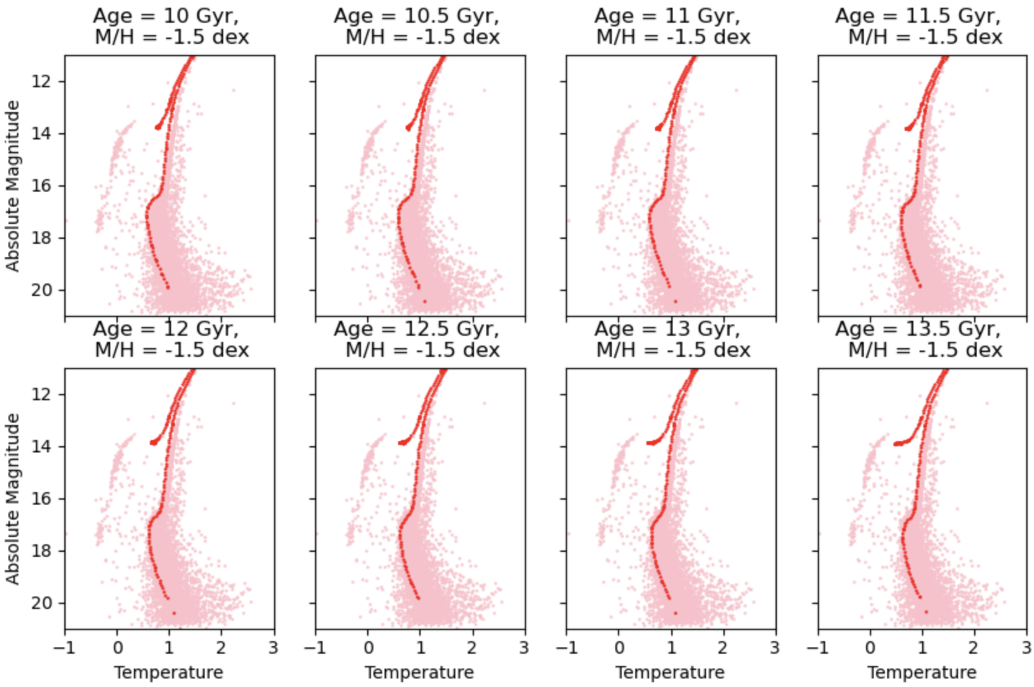
Given that the clusters are estimated to be aged in the range of tens of billions of years, we conducted an age analysis spanning from 10 to 13.5 billion years, adjusting in increments of half a billion years. For the assessment of metallicity, we explored a range from 0 to -1.5 dex, incrementing in steps of 0.3 dex. This method again resulted in a total of 48 isochrones, with 6 isochrones representing each age group. Subsequently, from the eight age groups explored, we identified eight isochrones that exhibited the closest fit to the HR diagram. Ultimately, among these top-performing eight isochrones, we pinpointed the one that demonstrated the most accurate fit, making it the best isochrone for the cluster

Here, we've presented plots representing ages of 11 billion years and 12 billion years. Comparable plots were obtained for other age ranges as well.





After plotting for all 8 age groups, we found that isochrone corresponding to -1.5 dex metallicity is the best one for every age. Now we plot the 8 best graphs, and compared visually that which isochrone fitted perfectly among the 'bests'.



After carefully seeing all 8 graphs, isochrone with age 12 Gyr fitted very accurately with the HR diagram at turn-off points, Red Giant branch and Red clumps.

So, from this we found metallicity and age of the cluster. Now we have to find its distance from the Earth. For this, we used again magnitude and distance relation :

$$m - M = 5\log_{10}(\frac{dist}{10})$$

where, *dist* = distance of that object from Earth in parsec.

To make the isochrones overlap on HR diagram, we added 13.5 in absolute magnitude. So *m* - *M* = 13.5. So,

$$dist = 10 * 10^{13.5/5} = 5011pc = 5kpc$$

which is close to the actual value.

3.4.4 47 Tucanae

47 Tucanae is a globular cluster located in the constellation Tucana.It is the second brightest globular cluster after Omega Centauri and is about 4.45 kpc away from Earth and 120 light years in diameter. 47 Tucanace can be seen with the naked eye, with an apparent magnitude of 4.1. We will try to estimate it's age and metallicity by finding which isochrone best matches it's HR diagram. Also we can estimate the distance to this cluster by the difference between apparent and absolute magnitude.
We find the stars in the cluster by looking for clustering in the pmra/pmdec space. First we visually identify the pmra and pmdec limits then take values within $\pm 3\sigma$ of the mean.

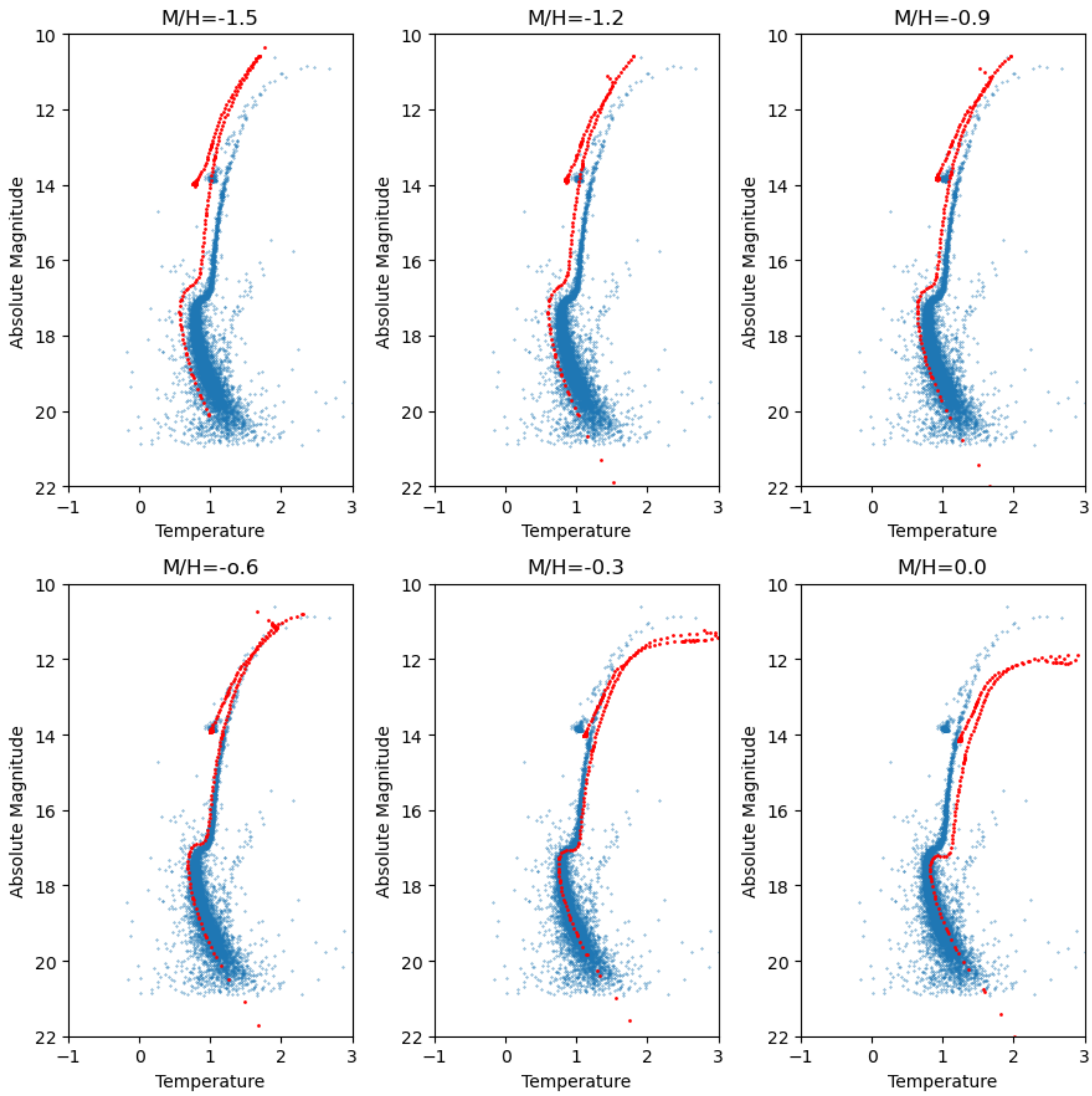


Figure 3.5: Isochrones of metallicities from -1.5 dex to 0 with a step of 0.3 dex

We find that the isochrone corresponding to metallicity = -0.6 dex best matches the HR diagram.

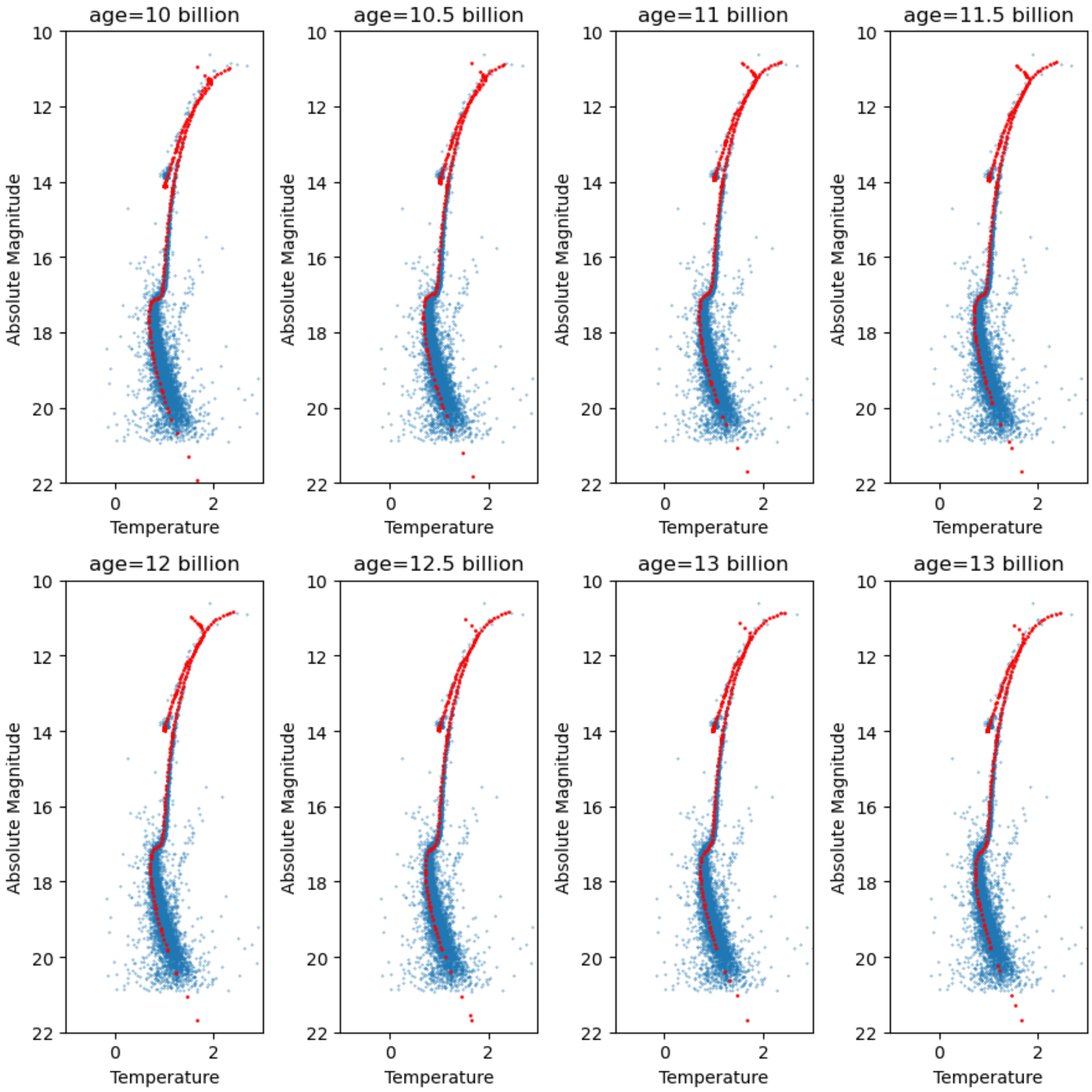


Figure 3.6: Isochrones of age from 10 billion years to 13.5 billion years with a step of 0.5 billion years and metallicity = -0.6 dex

We find that the isochrone corresponding to age = 12.5 billion years best matches the HR diagram.
The difference between apparent and absolute magnitudes is 13.5. Distance in paresecs is

$$10^{(13.5+5)/5} = 5011.87pc$$

4. Results and Discussion

In the 1st chapter, we made our concepts clear and theoretically understood what is necessary for the next two chapters stuff. We discussed about different coordinate systems, apparent and absolute magnitude scales, and the most important thing - HR diagrams. We learned about the life cycle of stars, their evolution track according to their masses.

Next, in 2nd chapter, we briefly discussed about the star clusters, especially open clusters, with some examples of Beehive cluster, Butterfly cluster, Christmas Tree cluster and King Cobra cluster. We took top 10,000 brightest stars from the GAIA catalog with given part of the sky by giving their right ascension and declination coordinates.

Let's take the example of Beehive cluster. By providing its coordinates, we plot the graph of apparent magnitude of stars with corresponding distance from Earth. We found some stars clusters at some 150 pc distance. We filtered that out and plot that cluster with proper motion ra and dec, and found a bunch of stars in a corner.

When we realized that stars arrangement with respect to the distance from Earth is some sort of Gaussian distribution (and it should be), we tried to fit a gaussian curve around this. Then $\pm 3\sigma$ clipped that data, as almost all stars are inside that $\pm 3\sigma$ vicinity around the mean.

Same thing we did for Butterfly cluster, Christmas Tree cluster and King Cobra cluster. Though we don't get as good distribution of stars in this cluster as in Beehive cluster, but still got good result for this. We went one step further to find its HR diagram and to find the fraction of stars of different stellar type. We found that **most of the stars are of G, K and M type** with K stars dominating the cluster. Also by seeing the HR diagram, we saw that most of the stars are in Main Sequence. This made us understand that almost 90% of the stars are living and will live their life silently with surface temperature nearly as of our own Sun for 100s of million years, or even some billion years also.

After studying the open clusters, we moved towards the globular cluster part. The main aim of that section, and also of this project was to analyze various globular clusters by making its HR diagrams and inferring its age and metallicity, with an addition of finding their distance from Earth.

As discussed there and we know that globular clusters are very far away from us, we took range of distance from infinitely high to some very big distance. Because of this distance, their brightness will be very low, so instead of taking 10,000 brightest stars, we took every star of the GAIA catalog with some contraints of distance and renormalised unit weight error.

To find their age and metallicity, we used different isochrones with a range of ages and metallicities, and tried to find the best among the all.

Let's take example of M3. Similar to the open cluster, we plotted the graph of apparent magnitude of different stars against their distance, and as expected, we found no cluster. We plotted their HR diagram with that data only (to get more clear diagram, we could use $\pm 3\sigma$ clipping for pmra and pmdec, as we did in Omega Centauri cluster).

We then used isochrones of ages between 10 billion years and 13.5 billion years, and with metallicity between 0 *dex* and -1.2 *dex*. For every age group, we found the best fitted isochrone. In our case, that was of -1.2 *dex* metallicity isochrone. After finding best fit for each age group, we found visually that for what age, we would get the perfect isochrone. For M3, we found that **11.5 billion years** and **-1.2 *dex*** fits the best with its HR diagram.

Actual age of M3 cluster is 11.4 Gyr, which is in very good range of approximation.

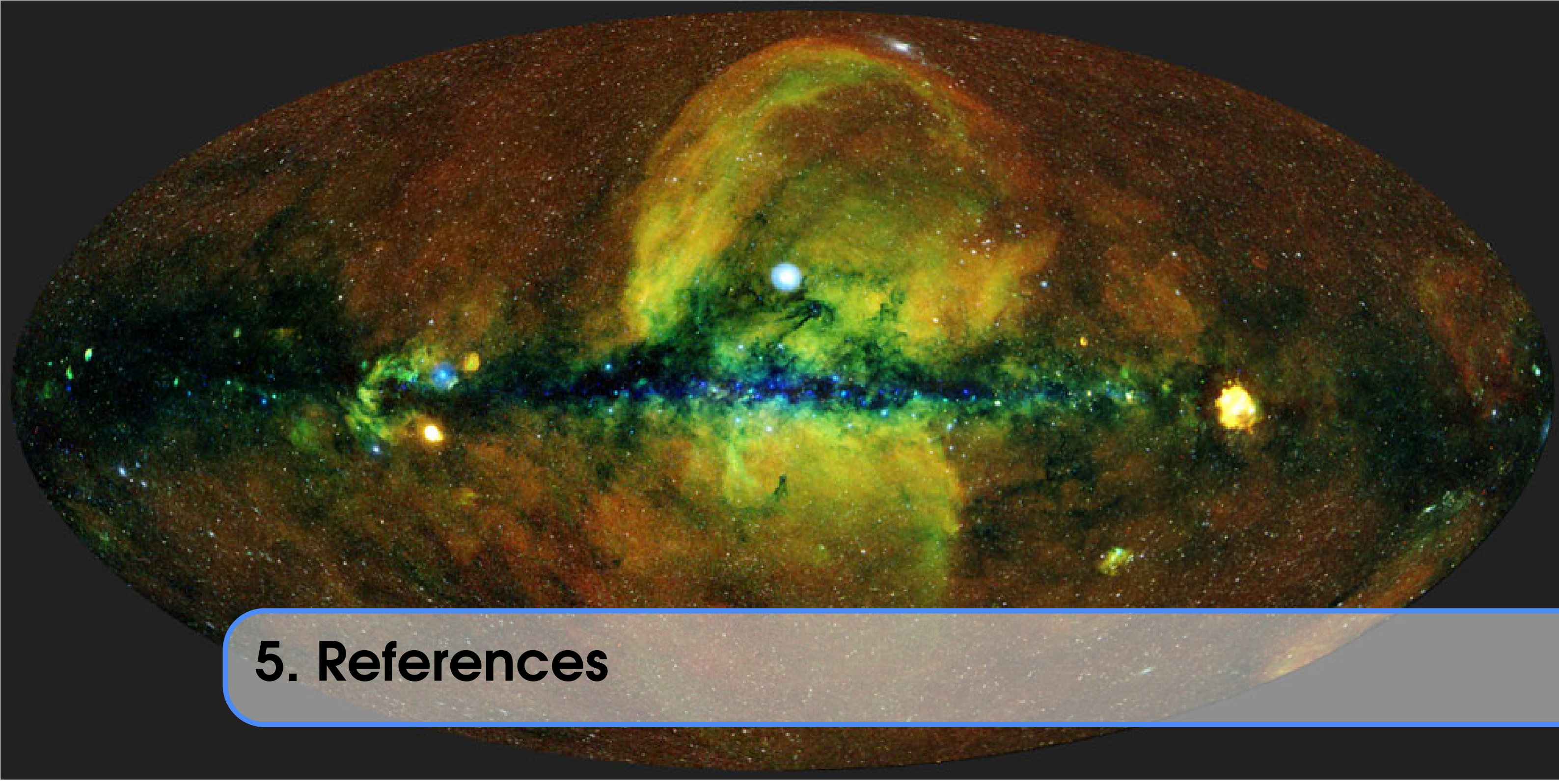
To find distance, we used magnitude-distance relation. When we plotted only isochrone, that was the graph between **apparent magnitude** and distance. To make it fit with HR diagram, we added some number in the apparent magnitude, and that number was the difference between the absolute magnitude and apparent magnitude. For M3 case, that difference was 15. We used that in the relation and found **the distance between Earth and M3 cluster is 10 kpc**, which also very accurately matched with the actual value.

Same thing we did for NGC 6752 cluster and we found that **12 billion years** and **-1.5 *dex*** fits the best with its HR diagram.

Actual age of NGC cluster is 11.78 Gyr, which is in very good range of approximation.

For NGC 6752 cluster case, the difference between the absolute magnitude and apparent magnitude came out to be 13.5. We used that in the relation and found **the distance between Earth and NGC 6752 cluster is 5 kpc**, which is in very good range of the actual distance i.e. 4 kpc.

And that was our aim in this project. We found the metallicity and age of the globular cluster with a great accuracy with actual value.



5. References

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