Prerequisites for estimating the age of star clusters

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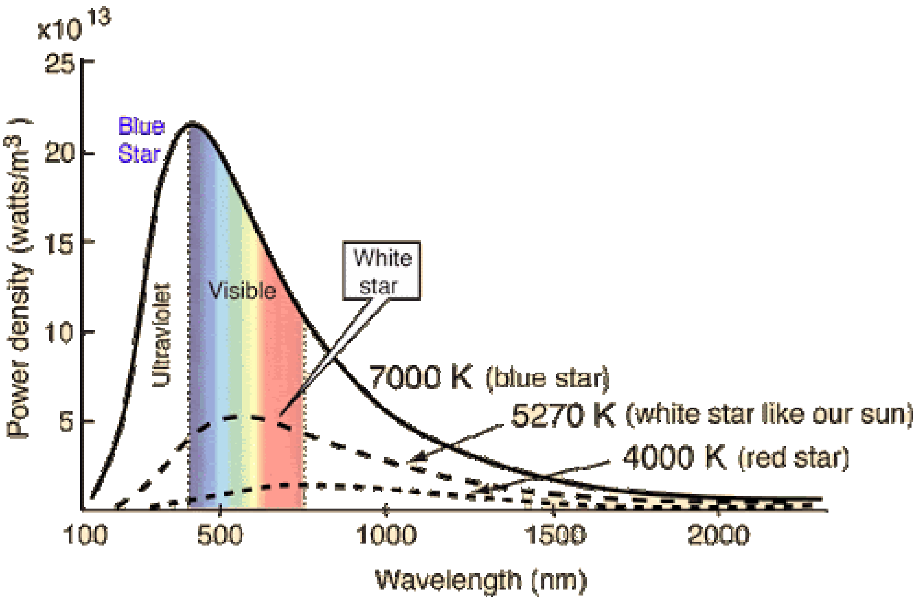
Introduction:

The aim of our project is to estimate the age of star clusters and there are some concepts that are crucial to understand and implement our objective. The fundamentals of stellar astrophysics involve concepts such as spectral emissions, black body radiation, stellar classification of stars, Hertzsprung–Russell diagram and colour magnitude diagrams. In this report, the basics of these topics are discussed in a more qualitative fashion.

Spectral Emissions and Black Body Curve:

All objects (in the macroscopic sense) emit and absorb electromagnetic radiation, in fact, any object with temperature above absolute zero emits thermal radiation, which is just EM radiation produced by thermal motion of particles in matter. When EM radiation is incident on a body, it could be absorbed, reflected or it could just pass through the body unaffected. Generally, a combination of the three phenomena occur for any body and this affects observable properties like power, colour, temperature etc. To start studying these properties, we should start with the ideal body; a black body.

A black body is an object that absorbs all wavelengths of light that falls on it. Since it absorbs any radiation incident on it, there is no chance of reflection or transmission. We've also established that all objects emit radiation, this means that a black body in thermal equilibrium must also emit the same amount of energy incident on it. Thus, a black body is also a perfect emitter. It emits a characteristic spectrum that depends only on temperature and spans all electromagnetic wavelengths. This was explained by scientists in the early 20th century, with Planck being at the centre of the spotlight.



There are two major takeaways from the studying of black body curves (Intensity vs Wavelength):

1) Stefan-Boltzmann's law: The amount of radiation emitted per unit time from an area A of a black body at absolute temperature T is directly proportional to the fourth power of the temperature.

$$P=\sigma T^4$$

where σ is Stefan's constant = 5.67 × 10-8 W/m2 k4

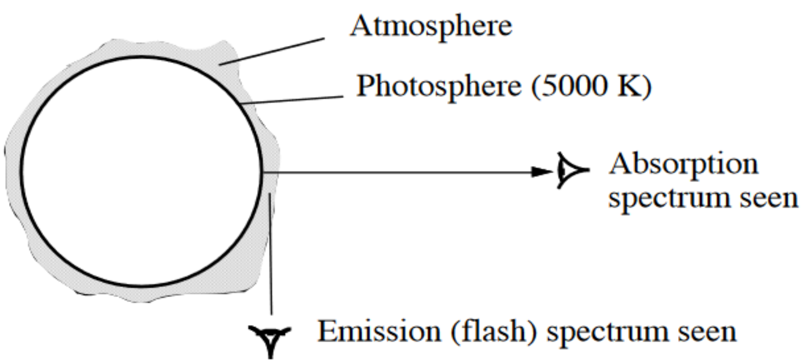
2) Wien's displacement law: Black body radiation curve for different temperatures peaks at a wavelength inversely proportional to the temperature. In other words,

$$\lambda_{max} T=constant$$

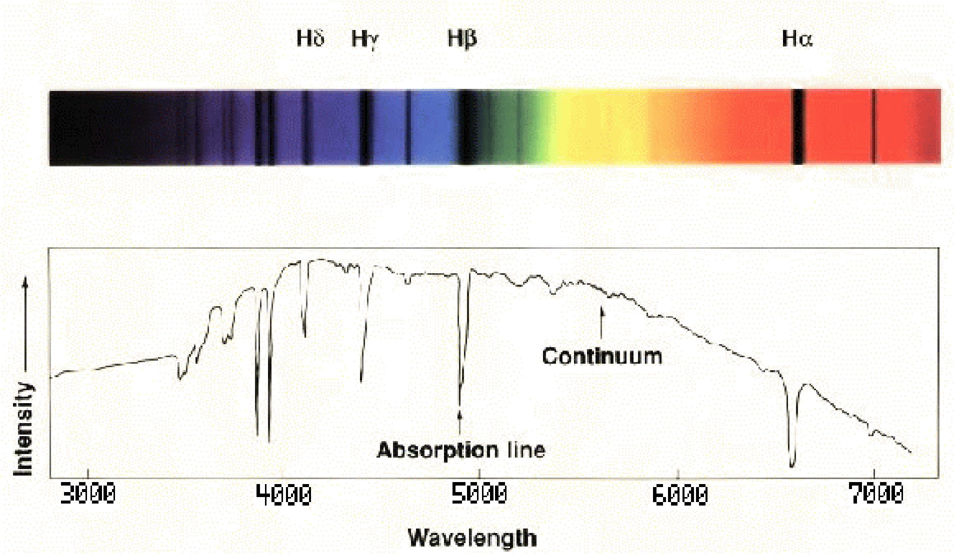
If we observe the spectrum of stars, it seems to fit the black body curve arguably well. A star can be approximated as a black body because almost all the light that we get from it is emitted due to its temperature and there is minimal reflection of light from other sources. This means we can use black body laws to study stars.

A star can be modelled as hot ball of gas with a very hot, dense interior (the photosphere is where we consider this region to begin) and a cooler, less dense outer layer. A continuous spectrum (black body curve) is produced due to the high temperature and opaque interior of the star. The outer layer is a cooler gas which is unionised and can absorb certain wavelengths of photons coming from the interior. This leads to absorption lines in the spectrum. These absorption lines are of major importance as we use them for the classification of stars. An emission spectrum is also produced by the gas in the outer layers as the temperatures are high enough to allow electron energy transitions.

A diagram of this star model for the sun is shown below.



An example of what the actual spectrum of a star would look like. The continuum isn't as smooth because of noise.



Stellar Classification:

In an effort to expand the *Horizons* of our knowledge of the cosmos, astronomers took up the task of categorising stars. The most 'obvious' difference in stars is probably their brightness. Classifying stars on the basis of their brightness was initiated way back in the times of Hipparchus (190 BC-120 BC). He developed a scale for stars based on visual brightness, which eventually became quantified as stellar magnitude. Later as apparatus got better, there was another basis for categorising stars which was realised, colour. Colour may seem quite ambiguous as a parameter but it is dependent on temperature, which is well defined.

Astronomers initially thought the difference in spectra among stars was due to different chemical compositions but Cecilia Payne-Gaposchkin showed that stars are made up of mostly hydrogen and helium with slight variations in the abundance of other elements in fixed compositions. The difference is actually due to surface temperatures.

The star is assigned a spectral type, which is represented by the letters O, B, A, F, G, K, and M, arranged from highest to lowest temperature. These are the main 7 spectral types and there are a few more. Within each type are 10 subtypes numbered from 0 to 9. For example, A3 is hotter than A4 but cooler than A1. Sun is a G2 star.

How are absorption lines related to these types? O stars have the highest temperatures, which makes it possible to ionize once Helium which requires a lot of energy. Also, at this temperature, since hydrogen is ionized, there is no possibility for absorption lines. Hence, H lines are very weak in O stars. A, B and F stars have enough energy to energize their hydrogen but not ionize, so H lines are very strong. Metals are easy to ionize so they don't require very high temperatures. In very cool M stars, the atmosphere is cool enough to have molecules such as TiO that produce molecular spectra.

There have been new additions to the types such as W (Wolf-Rayet stars), L (cooler than M), T (brown dwarfs), Y, C (Carbon stars) and many more.

Type	**Color**	**Approximate Surface Temperature**	**Main Characteristics**	**Examples**
O	Blue	> 25,000 K	Singly ionized helium lines either in emission or absorption. Strong ultraviolet continuum.	10 Lacertra
B	Blue	11,000 - 25,000	Neutral helium lines in absorption.	Rigel Spica
A	Blue	7,500 - 11,000	Hydrogen lines at maximum strength for A0 stars, decreasing thereafter.	Sirius Vega
F	Blue to White	6,000 - 7,500	Metallic lines become noticeable.	Canopus Procyon
G	White to Yellow	5,000 - 6,000	Solar-type spectra. Absorption lines of neutral metallic atoms and ions (e.g. once-ionized calcium) grow in strength.	Sun Capella
K	Orange to Red	3,500 - 5,000	Metallic lines dominate. Weak blue continuum.	Arcturus Aldebaran
M	Red	< 3,500	Molecular bands of titanium oxide noticeable.	Betelgeuse Antares

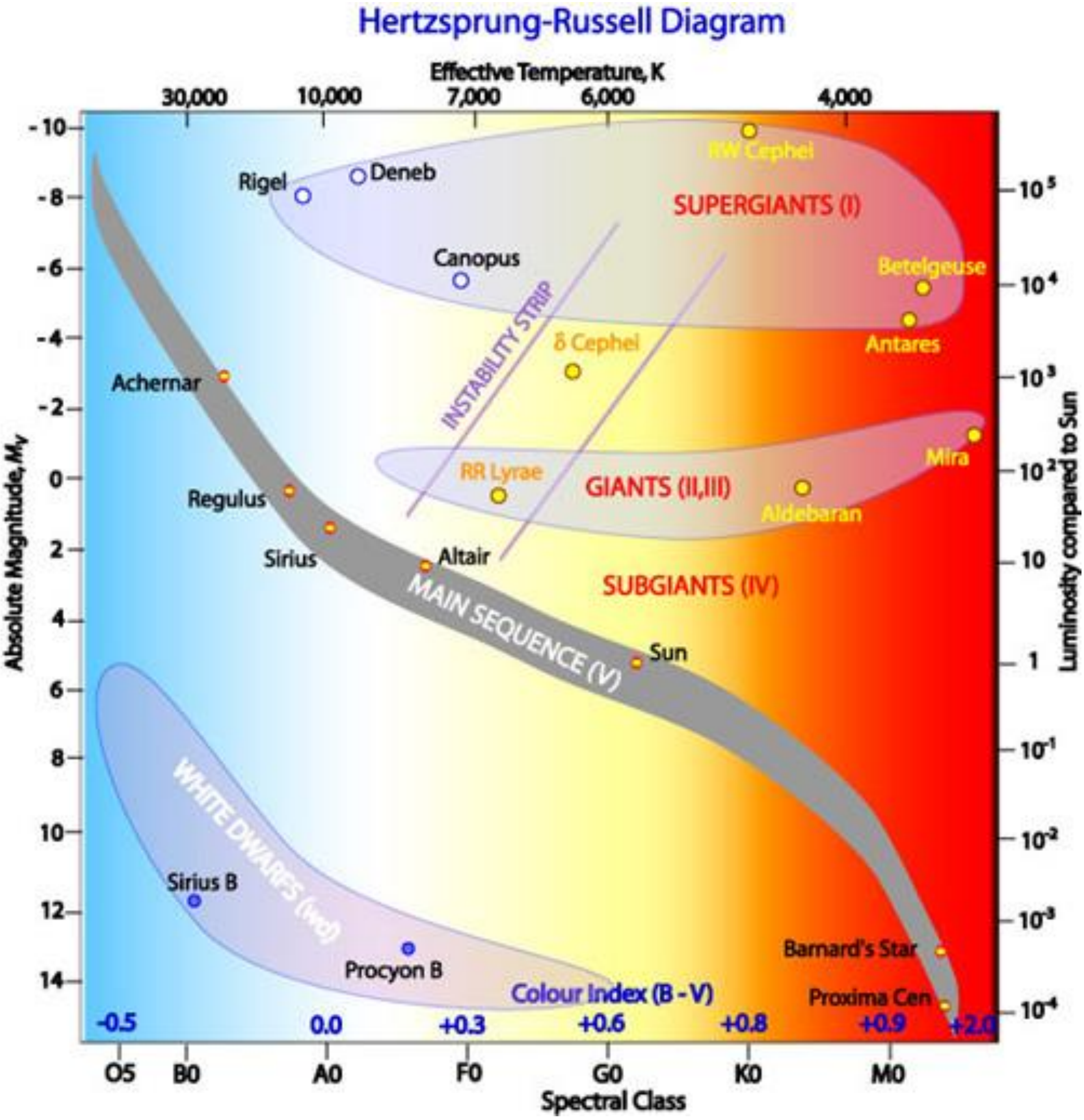
There is another classification scheme called Luminosity Classes. Luminosity is the total energy that a star produces in one second ($L = 4\pi R^2 \sigma T^4$). For a given temperature, some stars are more luminous than others due to larger sizes. More luminous stars have narrower spectral lines. The classes are assigned based on the width of the spectral lines. For a group of stars with the same temperature, luminosity classes differentiate between their sizes.

Luminosity Classes:

Ia	Most luminous supergiants
Ib	Less luminous supergiants
II	Luminous giants
III	Normal giants
IV	Subgiants
V	Main sequence stars (dwarfs)

Hertzsprung-Russell Diagram:

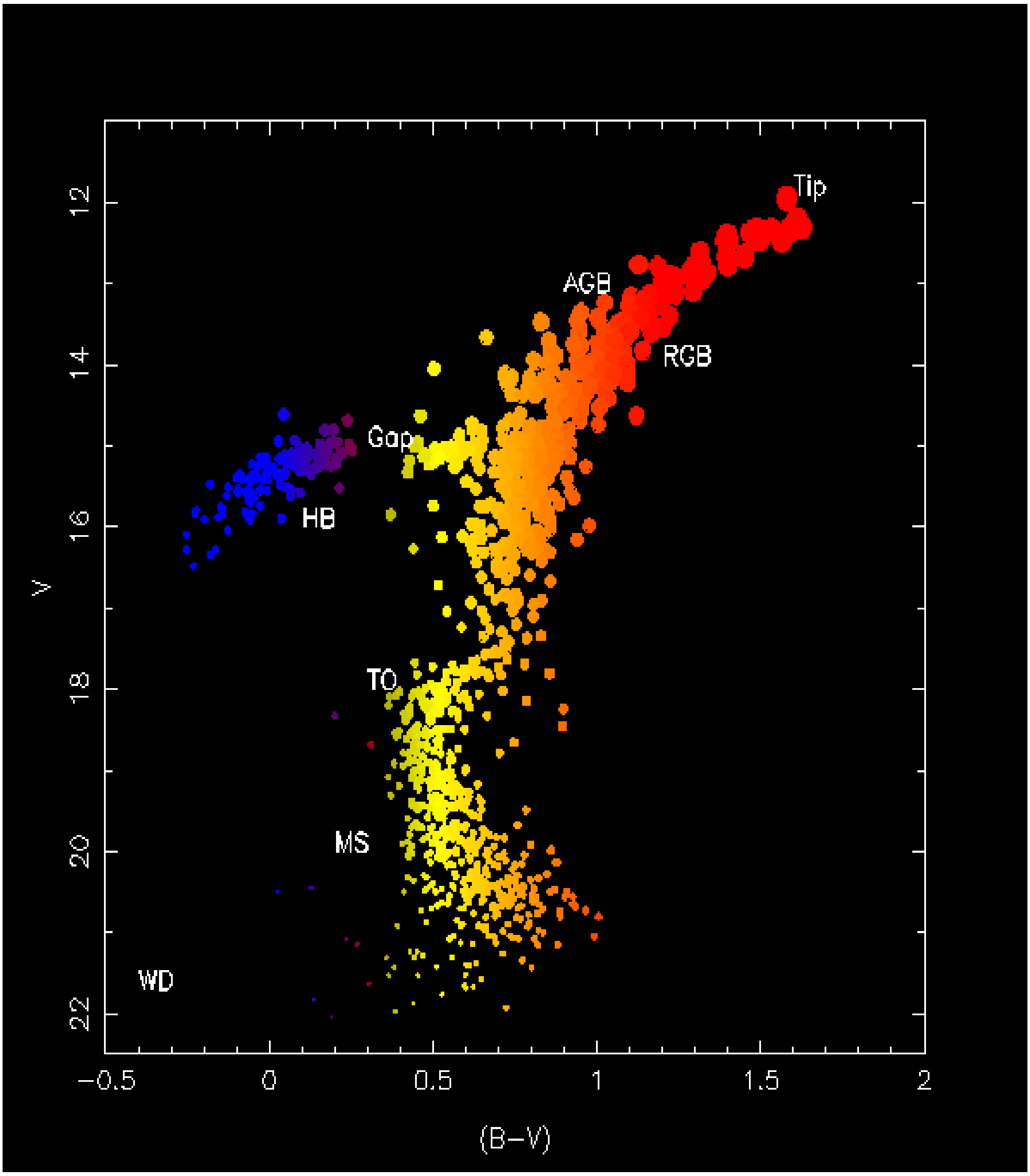
It was first conceived when the Danish astronomer, Ejnar Hertzsprung, plotted the absolute magnitude of stars against their colour (hence effective temperature). Henry Norris Russell also plotted a similar graph. Their plots showed that there was a relation between luminosity and temperatures and the stars followed particular trends. The temperature actually decreases from left to right in an HR diagram. Absolute magnitude is just another way of measuring luminosity as it doesn't vary with distance from the star.



Most stars fall under the main sequence of stars. Even the Sun is part of this group. In the main sequence, the stars are using hydrogen as fuel in a stable manner. Here, high luminosity relates to high temperature. Larger stars exert more pressure on the core, leading to more nuclear fusion. Hence, massive stars are more luminous. (True only for main sequence)

HR diagram shows the lifetime of a star. In its final stages, stars move from the main sequence to the other groups. Where the star ends up is dependent on its mass. A giant or supergiant has more luminosity than a main sequence star of same temperature.

Colour Magnitude Diagram:



CMD for globular cluster M5.

While studying stellar evolution of bodies, star clusters are very useful to astronomers. Stars are born in large, deep molecular clouds and eventually form gravitationally bound groups which are called star clusters. There are two major types of clusters, globular and open.

- Globular clusters are tight groups of hundreds to millions of old stars which are gravitationally bound and exist in the halo of the galaxies where they not being disrupted and are stable.
- Open clusters, more loosely clustered groups of stars, generally contain fewer than a few hundred members, and are often very young.

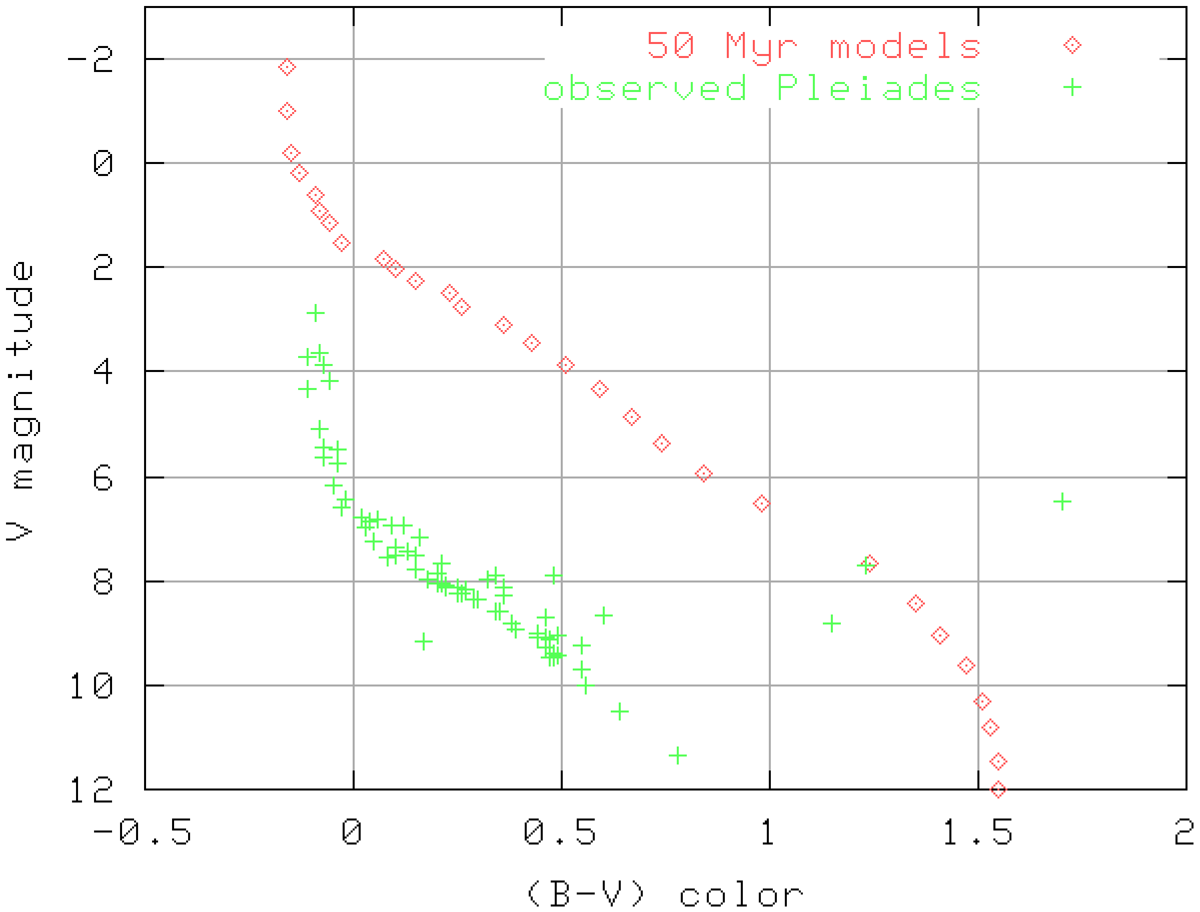
Globular clusters provide us very useful information as the stars have similar chemical compositions and similar ages due to common origin. Furthermore, these are some of the oldest heavenly bodies which help us peek into the origins of our universe and also stellar formation. The stars of a cluster differ in their respective masses. If we were to study this system using a HR diagram, there are many ways we can optimise the plot.

- Each star in a cluster is at roughly the same distance from us. This means the apparent magnitude of a star is proportional to the absolute magnitude. We need not know the distance between the cluster and us. In fact, we can actually find this distance from the CMD.
- Instead of actually measuring temperatures by acquiring the spectrum of multiple stars, we use Colour Index (CI). Colour is defined as the difference between the magnitude of a star in one passband and the magnitude of the same star in a different passband. The most common passbands used are B and V bands (centred at 440 & 550 nm, respectively). What does this mean? B-V colour index is related to the logarithm of the ratio of intensities at each wavelength and this is directly related to the temperature from the black body curve. When B-V is negative, the apparent magnitude in B band is lesser than that in V band. Thus, the star has a higher intensity of blue light, which makes it bluer. Similarly, if B-V is positive, the star is redder. Redder stars have lower effective temperature than bluer stars.

In this manner, we can plot a variation of the HR diagram with the horizontal axis as B-V (or any CI of our choice) and apparent magnitude of stars (even at a particular wavelength). This is called a Colour Magnitude diagram.

Just like the HR diagram, the CMD has regions corresponding to different star types. In the diagram above, a few regions are the Main Sequence (MS), Turn off (TO), Red Giant Branch (RGB) etc. MS stars are burning hydrogen in a stable manner whereas the TO region corresponds to the stars which have run out of hydrogen and start to deviate from the MS. After the TO region, some stars move to RGB where they become larger but cooler due to processes in the core. Hence, the CMD can show the many stages of stars.

CMD of a cluster changes as time progresses. Isochrones are theoretical models of the CMD branches at a given age, for a given chemical composition. At a particular age, we can compare our isochrones with the observed CMD and check whether they fit each other. In this manner, we can estimate the age of star clusters.



Contrasting the CMD of Pleides with an isochrone (in red). They match pretty well, indicating the age of Pleides could be 50 million years.