The Hertzsprung-Russell Diagram

INTRODUCTION + AIMS

You will use the observational and analysis tools of modern astronomy, mimicking the setup that professional astronomers see when they use a large telescope, via VIREO - the Virtual Educational Observatory.

You will produce and compare Hertzsprung-Russell diagrams of star clusters. You will use the telescope to calculate the magnitudes and colours of individual stars in the clusters. You will fit a zero-age main sequence to estimate the distance to the cluster, and an isochrone to estimate the age of the cluster. You will compare your estimations to other clusters and to the literature values.

If you come across a word or phrase that you do not understand, consult the glossary at the end of this manual. Throughout the manual, the words and phrases included in the glossary are in **bold***.*

You will find questions throughout the workshop. To answer the questions, use your own knowledge, the glossary, or conduct independent research in the scientific literature (online or in a textbook).

Installing the Software

IMPORTANT - the VIREO software is only available on Windows operating systems.

Go to: http://www3.gettysburg.edu/~marschal/clea/CLEAhome.html
On the left-hand menu, select `Software`, then scroll down and select `HR Diagrams of Clusters`. On the right-hand side, click `VIREO.zip`, and save it in the desired location. Warning: the program may take up to an hour to download, depending on the speed of the connection. The software should be installed on each computer to be used for the workshop, prior to the workshop. Alternatively, it is possible to install the software onto a server/network for access by individual workstations. For more information, visit the CLEA webpage above.

Students will also require access to the internet to research the star clusters, however the necessary information could be alternatively provided. See the Help Sheet for more details.

THEORY

The Hertzsprung-Russell Diagram

A **Hertzsprung-Russell diagram** (HRD) is one of the most useful tools that astronomers use to study the evolution of stars. Typically, HRDs are plotted as the temperature of the star against its luminosity.
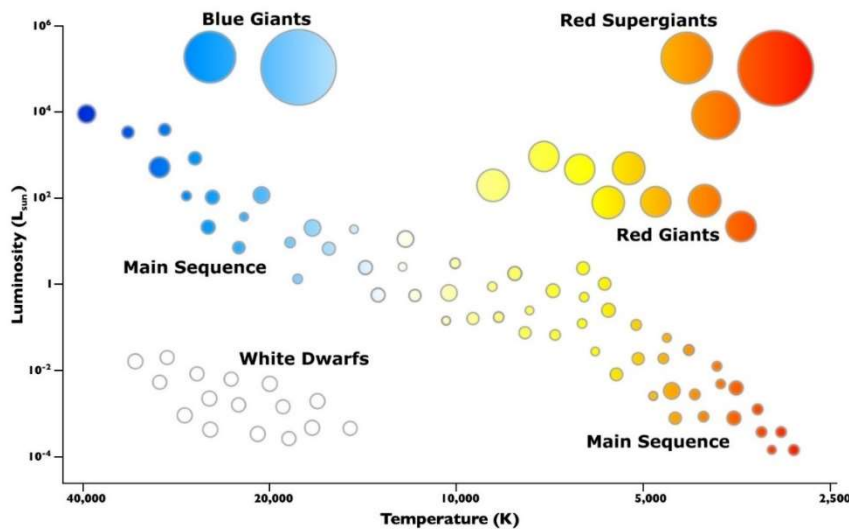
The Hertzsprung-Russell diagram.
Source: https://lco.global/files/jbarton/HR%20Diagram(units).jpg

An alternative way to present the same information is via a **colour-magnitude diagram** (CMD). Here, the **colour index** of a star (typically *B-V*) is plotted against its **absolute magnitude** (typically in the V filter). The brighter a star is, the more negative its **magnitude**. For example, a star with *M*=-2.5 is brighter than a star with *M*=+2.5.

In the diagram, the hottest, brightest stars lie in the upper left, and the coolest, dimmest stars lie in the lower right. Stars in the upper right of the diagram are extremely bright despite having low surface temperatures. This requires the stars to have large surface areas; these are the red giants and supergiants, with radii many times that of the Sun. Stars in the lower left of the diagram are extremely faint despite their high temperatures; these stars are small, with radii much smaller than that of the Sun, and are known as white dwarfs.

The most common stars are those on the **main sequence**, the region where stars spend the majority of their lives. Main sequence stars burn hydrogen into helium, via nuclear fusion, in their cores. The position of a star on the main sequence depends on its mass. The lower mass stars (from the mass of the Sun down to about 0.08 solar masses) are cooler and dimmer, and occupy the lower right of the main sequence. The higher mass stars (from about 2 to 50 solar masses) are hotter and brighter, and occupy the upper left of the main sequence.
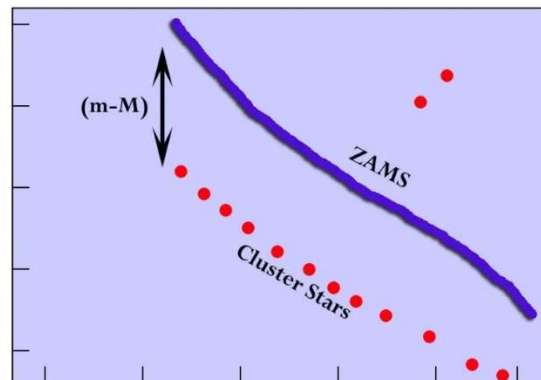
Star Clusters

Star clusters are simply groups of stars. There are 2 types of star clusters: **open clusters** and **globular clusters**. Globular clusters are tight groups of ancient stars, and are poorly understood. Open clusters, however, are an incredibly useful tool for astronomers. It is believed that all of the stars in an open cluster formed from the same collapsing cloud of interstellar gas, and are roughly the same age. Open clusters tend to be much smaller and younger than globular clusters. The stars within a cluster have a range of stellar masses, and so when the cluster is young (and its stars have just begun to fuse hydrogen into helium in their cores), the stars will all lie along the **main sequence**. This forms the **zero-age main sequence** (ZAMS).

Distance to Star Clusters

It is possible to use **HRD**s (or **CMD**s) to determine the distance to a star cluster. All of the stars in a cluster are roughly the same distance from us, and their light is dimmed according to that distance. A diagram of the **apparent magnitudes** of the stars against their **colour indices** is plotted for the star cluster, forming an observational CMD. Typically, the apparent magnitude used is that through the yellow **filter**, which is written as V. The colour index used is then B-V.

The resulting main sequence is compared to the ZAMS (which is plotted using **absolute magnitudes** M, instead of apparent magnitudes m), and the difference between the apparent and absolute magnitudes can be calculated: this is the **distance modulus**, m-M. In the V filter, the distance modulus is written as V-M_v. The distance D to a cluster (in **parsecs**) can be calculated using the formula:
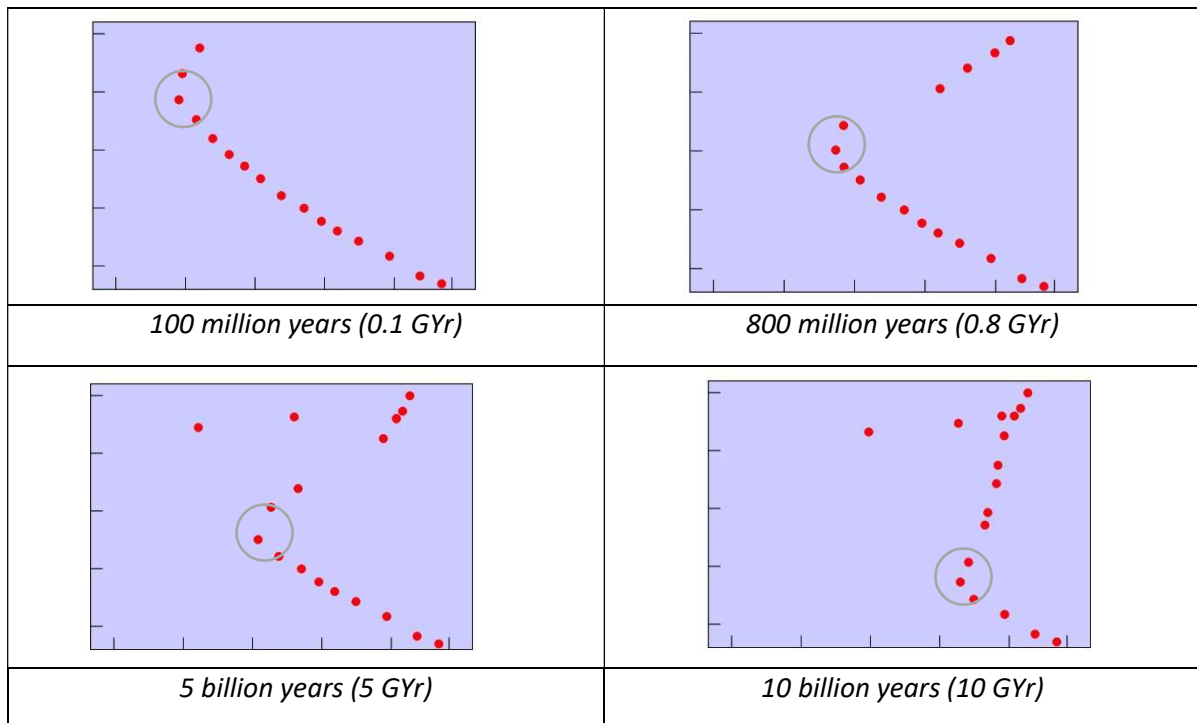
$$\log_{10} D = \frac{m-M}{5} + 1.$$

The Hertzsprung-Russell (or colour-magnitude) diagram showing the observational data from a star cluster (red points), and the zero-age main sequence (ZAMS). The distance modulus m-M *is indicated. Source: CLEA manual HRdiag_sm.doc*

Aging of Star Clusters

As a star ages, it begins to run out of hydrogen fuel in its core. Hydrogen then begins to burn in a shell around the core, and the star expands and cools, becoming a red giant. The first stars to become red giants are the most massive stars in the cluster, followed by the less massive stars. Therefore, as a cluster ages, the **main sequence** gets shorter and the red giant region becomes increasingly populated (as shown in the diagrams below). The **main sequence turnoff point** is indicated in the diagrams by a grey circle.

Astronomers use the length of the main sequence to estimate the age of a cluster. By comparing the **HRD** observed to a computer model called an **isochrone**, it is possible to precisely determine the age of a star cluster.

100 million years (0.1 GYr)	*800 million years (0.8 GYr)*
5 billion years (5 GYr)	*10 billion years (10 GYr)*

The changing shape of a Hertzsprung-Russell (or colour-magnitude) diagram as a star cluster ages.
The grey circles indicate the main sequence turnoff point.
Source: CLEA manual HRdiag_sm.doc

Alice Perry, Ogden Student Intern, July 2017

METHOD

Setting up the Telescope

- Double click `VIREO` to open the program.
- Click `File` → `login`, and type your name as Student #1, then `ok` and `yes`.
- Click `File` → `Run exercise` → `HR Diagrams of Star Clusters`.
- Now, you need to access a telescope to observe the star clusters.
  Click `Telescopes` → `Optical` → `Access 0.4 Meter`.
- You should see the inside of the telescope dome. Click the switch to open the dome.

What is the wavelength range of an optical telescope?

_____

Locating the Star Cluster

- Select the first star cluster to observe, The Pleiades:
  Click `File` → `Cluster Data` → `File` → `View/Select Cluster from List`.
  Double click on `M45 (Pleiades)`, then click `ok`.
  A list of 297 stars in the star cluster should appear, alongside their positions in the sky.
- Click `Selection` → `Create New Hot List of Entire List` → `ok`.
  Now, close this list of stars.
- Turn the `Telescope Control Panel` on.
- The field-of-view of the telescope changes with the rotation of the Earth. This will make observing the star clusters very difficult, and so the telescope needs to account for the Earth's rotation to track the stars in the sky. Turn on `tracking`, so that the light turns green. You should notice that the field-of-view of the telescope now stays fixed.

Observing the sky from the Northern hemisphere, which star remains fixed in the sky whilst the other stars rotate around it? In which direction do they rotate?

_____

- Now we need to slew (move) the telescope to the target location in the sky.
  Click `Slew` → `Observation Hot List` → `View/Select from List`.
  This will open a list of the stars in the Pleiades cluster. Double click on the first star in the list (named N2230-00614). Click `ok` then `yes`.
- The telescope has now located that particular star in the cluster. Switch the view from `Finder` to `Telescope`. You should now see a bright star in the centre of the field-of-view, inside a red circle. This red circle indicates the region inside which the **photometer** collects light.

Observing the Star Cluster - Sky Background Observation

- Access the `photometer`. The Photometer Control window will open; you will use this to make observations of the individual stars in the cluster.
- Before making an observation of an astronomical object, a '**sky background**' observation must be made. This is because the **photometer** measures all of the light it can see, which includes light from the star and light from the sky background. The program subtracts the light from the background, leaving only the light from the star - which is important for the analysis. Switch the reading to `sky`.
- Using the Telescope Control Panel, slew the field-of-view away from the central star. Move the telescope slightly N, E, S or W, so that the red circle contains a dark patch of sky. This should be roughly 2 red circle-diameters away from the central star, in any direction.
- In this observing session, we will use the B and the V **filters**. Switch to the Photometer Control window. Firstly, make a 'sky background' observation using the V filter: ensure that `Filter` is set to `V`. As a standard, we set the **integration time** to be 10.0 seconds, and we complete 3 integrations. You may need to adjust the sliders to these values.
- Click `Start` the integration. You must not move the telescope during the integration, and the integration must be complete before starting the next observation.
- There is a timer to display the duration of the observation, and a counter of the completed integrations. The red counter at the bottom is a running total of the number of **photon** counts. The number of photon counts in each integration is displayed as `Raw Counts`. The program also calculates the mean number of counts per second in each integration.
- Keeping the `Reading` set to `Sky`, repeat the process for the same dark patch, this time using the B filter. Again, the observation should be 3 integrations each of 10.0s duration.

Observing the Star Cluster - Stellar Observation

- Using the telescope Control Panel, slew the telescope back onto the star, so that it lies in the centre of the red circle.
- Switch `Filter` to `V`, and `Reading` to `Object`.
- Now, we need to set the duration of the observation. Try 4 integrations, each 1.0s long. The aim is to achieve a **signal-to-noise ratio** (`S/N Ratio`) in the range 100 - 200 for the observation to be successful. In this case, the `S/N Ratio` is approximately 105, which indicates a successful observation of the star.
- If the S/N ratio is too low, the noise in the observation is too high compared to the signal from the star; this will make the analysis inaccurate. For particularly dim stars, a S/N ratio of 70 or above is acceptable.
- You may need to adjust the integration parameters (`Integration Seconds` and `# of Integrations`) until a successful observation has been made. A longer integration allows more light into the telescope, and increases the number of **photon** counts. If you need to retake an observation, simply change the integration parameters, `Start` the integration, click `no` when asked to save/record the data, and then `ok`.
- Once a successful observation has been made, click `File` → `Data` → `Record/Review`, then `ok` and `ok`. The program has calculated the **apparent magnitude** of the star in the V **filter** from your observations.

***Think: what is the difference between the apparent magnitude
and the absolute magnitude of a star?***

▪ The observation of the star needs repeating in the B filter. Switch `Filter` to `B`. Try an observation with the same integration parameters as your successful V filter observation. Look at the S/N ratio to see if the integration needs adjusting. Once a successful B filter observation has been completed, click `File` → `Data` → `Record/Review`, then `ok` and `ok`. The program has now calculated the apparent magnitude of the star in the B filter from your observations.

Plotting the Hertzsprung-Russell Diagram

▪ In the main VIREO window, click `Tools` → `Results Editors` → `Observational Results` → `Display/Print/Save Text`. The results from your observation will be shown. There are columns displaying the V **filter** and B filter **magnitudes**, alongside other information about the star.

▪ The program uses the observational data to plot a **HRD**, or in this case a **colour-magnitude diagram** (CMD). The **colour index** *B-V* is plotted on the x-axis, and the **apparent magnitude** in the V filter is plotted on the y-axis. Look at the observational data you have taken, and predict the (*B-V*, *V*) coordinate of the star on the CMD:

Star N2230-00614	
V	
B	
B-V	
(B-V, V)	

▪ Close the Recorded Results window, and click `Tools` → `HR Diagram Analysis`.
▪ A CMD will appear on the screen. A single star will be plotted - this is the star from your observations! Confirm that it appears in the location that you predicted, by looking at the *B-V* and *V* values.
▪ Now, it is time to populate your CMD with observations of more stars in the cluster. Return to the Telescope Control Panel. Click `Slew` → `Observation Hot List` → `View/Select from List` to open the list of cluster stars.
▪ Double click on another star in the list - choose any star. Click `ok` then `yes`.
▪ Repeat the steps outlined in *Observing the Star Cluster - Stellar Observation*. There is no need to repeat the **sky background** observations, since the stars in the cluster are relatively close together in the sky. You should obtain values of the apparent magnitude in the V and B filter for your chosen star.
▪ To access these values, click `Tools` → `Results Editors` → `Observational Results` → `Display/Print/Save Text`. Record your results in the table below:

Star N2230-_____	
V	
B	
B-V	
(B-V, V)	

- In the CMD window, click `File` → `Load/Plot` → `Data from Observations`. A second point should appear on the CMD, at the (*B-V*, *V*) coordinate of the second star observed in the cluster.
- Repeat the process for 3 more stars in the cluster (or until further instructions from your teacher/supervisor). Each time, add them to the CMD as above. You should see the **main sequence** beginning to emerge in the diagram.
- It would take many hours to manually observe and plot each star in the cluster. In the CMD window, click `File` → `Load/Plot` → `Select Cluster Data`, and double click on `M45 (Pleiades)`. The completed CMD should appear, containing 297 stars.

Part 1 - Distance to the Star Cluster

- Click `Tools` → `Zero-Age Main Sequence` to plot the **ZAMS** on the cluster **CMD**.
- On the right of the CMD window, there is a slide-bar to control the **distance modulus**, *V-M$_v$*. Increase the distance modulus until the ZAMS matches well to the middle of the **main sequence** on the CMD. For the Pleiades, the distance modulus is between +5.00 and +6.00 - see if you can get a better fit to the data with a more accurate value.

<p style="text-align: center;">***Distance modulus:*** _____</p>

- Using the distance modulus equation given before, calculate the distance to the star cluster, in **parsecs**. Record your answer below, and in the table over the page.

<p style="text-align: center;">***What is the distance to the Pleiades cluster?***</p>

<p style="text-align: center;">_____ parsecs   _____ lightyears</p>

- Conduct some independent research in the literature (online or in a textbook) to find an accurate distance to the Pleiades cluster. Compare this value to the value you have calculated.

Think: why might the distance to the cluster you have calculated differ from the literature value?

Part 2 - Age of the Star Cluster

- Click `Tools` → `Isochrones` to plot an **isochrone** on the **CMD**. The isochrone parameter window should appear.
- There are two slide-bars to adjust to obtain a good fit of the isochrone to the data. The upper slide-bar adjusts the age of the isochrone, and the lower slide-bar adjusts the *B-V* value of the isochrone. A key feature to match is the **main sequence turnoff point**, at the left end of the main sequence. These stars are the first in the cluster reach the end of their **main sequence** lifetimes. The red giant phase of evolution is much quicker than the main sequence, and so there will be relatively few red giant stars compared to main sequence stars.
- The data for stars on the main sequence will be much more scattered than the sharp isochrone line. Some of this scatter is intrinsic to the cluster: for example, **binary stars** are brighter than individual stars at the same distance, which thickens the main sequence. More importantly, not all of the stars in the cluster are exactly the same distance from us. You will obtain a more accurate age by matching the isochrone to the lower edge of the main sequence, to avoid some of these outliers.
- You can also adjust the **metallicity** of the stars in the cluster. By default, this parameter is set to the solar values. Different values of the metallicity may improve the fit of the isochrone, but it is usually easier to maintain the solar values and focus on adjusting the age of the cluster.
- Once the best fit has been found, read off the age of the cluster, given in GYr (10^9 years). Record your answer below, and in the table further down the page.

Age of the Pleiades cluster: _____

- Conduct some independent research in the literature (online or in a textbook) to find an estimate for the age of the Pleiades cluster. Compare this value to the value you have calculated.

Think: why might there be an uncertainty in the age of the cluster determined by this method?

Think: how does the age you have calculated compare to the age of the universe?

Part 3 - Comparison of Star Clusters

- Once you are satisfied with the fit of the **ZAMS** and the **isochrone**, print a copy of your **CMD** for the Pleiades star cluster (`File` → `Print`).
- Click `Tools` → `View/Print Parameters`. Record the parameters you have selected in the table below:

The Pleiades	
V-M$_V$	
Distance to cluster	
Estimated cluster age	
B-V adjustment	

- Now, we will compare this CMD to that of a different star cluster, the Hyades. In the CMD window, click `File` → `Load/Plot` → `Select Cluster Data`, then double click on `Hyades`.

Consider the shape of the CMD for the Hyades.
Do you expect the Hyades to be older or younger than the Pleiades, and why?

_____

_____

_____

- Repeat the steps outlined in *Part 1 - Distance to the Star Cluster* to fit the ZAMS. Then, repeat the steps outlined in *Part 2 - Age of the Star Cluster* to fit the isochrone.
- Once you are satisfied with the fit of the ZAMS and the isochrone, print a copy of your CMD for the Hyades star cluster (`File` → `Print`).
- Click `Tools` → `View/Print Parameters`. Record the parameters you have selected in the table below:

The Hyades	
$V-M_V$	
Distance to cluster	
Estimated cluster age	
$B-V$ adjustment	

- We will consider a final comparison. Click `File` → `Load/Plot` → `Select Cluster Data`, then double click on `M67 (NGC 2682)`.

Consider the shape of the CMD for M67.
What can be inferred about the age of the star cluster, and why?

_____

_____

_____

- Repeat the steps outlined in *Part 1 - Distance to the Star Cluster* to fit the ZAMS. Then, repeat the steps outlined in *Part 2 - Age of the Star Cluster* to fit the isochrone.
- Once you are satisfied with the fit of the ZAMS and the isochrone, print a copy of your CMD for the M67 star cluster (`File` → `Print`).
- Click `Tools` → `View/Print Parameters`. Record the parameters you have selected in the table over the page:

M67	
V-M$_V$	
Distance to cluster	
Estimated cluster age	
B-V adjustment	

- Consider the similarities and differences between the CMDs for the Pleiades, the Hyades, and M67. Compare these similarities and differences to those in the parameters you have chosen for each cluster.
- Consider the CMD for the Hyades: there should be a population of stars in the lower left of the diagram. These stars do not belong to the **main sequence**, instead they are known as:

_____.

Think: what does this population of stars suggest about the age of the cluster?

Think: why is this population of stars not found in the Pleiades cluster?

EXTENSION + CONCLUSION

- If you have finished comparing the Pleiades, the Hyades, and M67, and have answered all of the questions throughout this manual, look at this extension task. Following the same method as before, analyse the **CMD**s of a further three star clusters. Record your results in the table below:

	$V-M_V$	Distance to cluster	Estimated cluster age	$B-V$ adjustment
Mel 20 Alpha-Persei				
M44 (NGC 2632)				
M7 (NGC 6475)				

Think: could you predict the relative ages of the clusters before fitting the isochrones?

- Finally, open the CMD of M16 (NGC 6611). Try to fit a **ZAMS** to the data. You will find it difficult to know where the ZAMS should sit on the diagram. M16 is a very young star cluster - only about 2 million years old! None of its stars are old enough to have evolved off the **main sequence**, and become red giants.

- The distance to the star cluster is 2150 **pc**. Use this information to calculate the **distance modulus**, and use the slide-bar to place the ZAMS in its correct location on the diagram. Would you have chosen this fit? M16 shows the limits of estimating the distances to star clusters using this method.

- Now, plot an **isochrone**. You will find it difficult to match the data - indeed, the cluster is so young that the software cannot fit an isochrone. The cluster is too young to have a **main sequence turnoff point**, and so M16 shows the limits of estimating the ages of star clusters using this method.

Think: how does the age of M16 compare to the age of our Sun, or the Earth?

- Conduct some independent research into the M16 star cluster, also known as the Eagle Nebula. Search for images of the cluster taken by the Hubble Space Telescope; you may recognise the incredible 'pillars of creation' photographs.

In this workshop, you have acted as a professional astronomer to calculate the distance to, and age of, several star clusters. You have interacted with a telescope as an astronomer would. You have taken data and analysed your data using software, as an astronomer would. You have conducted independent research to verify your results, as an astronomer would.

The VIREO software can be used in many different ways - take a look at the website to discover the other astronomy resources available: http://www3.gettysburg.edu/~marschal/clea/CLEAhome.html

GLOSSARY (A-Z)

Absolute magnitude (M or M_V):

The apparent magnitude an object would have if it was 10 parsecs away from Earth.

Apparent magnitude (m or V):

An object's magnitude as seen by the telescope on Earth.

Binary star:

A system of two stars orbiting each other. At great distances from a binary star system, it is impossible to see the individual stars, and instead they look like a single bright star.

Celestial coordinates, right ascension (RA) + declination (dec):

This is the coordinate system used by astronomers. Right ascension is equivalent to longitude, and declination is equivalent to latitude.

Colour index (B-V):

A way of representing the temperature of a star. *B-V* is the magnitude through the B filter, minus the magnitude through the V filter.

Colour-magnitude diagram (CMD):

The same as a Hertzsprung-Russell diagram, but its axes are colour *(B-V)* against magnitude *V*.

Distance modulus:

The difference between the apparent magnitude and the absolute magnitude of an object, *m-M*.

Filter:

A device placed in front of a telescope, only allowing certain wavelengths of light to pass through and be recorded. The V filter allows wavelengths in the range 450-650nm, which is yellow light. The B filter allows wavelengths in the range 360-520nm, which is blue light.

Globular cluster:

A tightly bound group of stars. Much older than open clusters.

Hertzsprung-Russell diagram (HRD):

A plot of luminosities against effective temperatures of stars.

Integration time:

The length of time that the CCD camera is switched on and collecting photons.

Isochrone:

A curve on the Hertzsprung-Russell diagram, representing stars of the same age.

Magnitude:

A measure of the brightness of an object. The brighter the object, the more negative its magnitude.

Main sequence:

A highly-populated band of stars on the Hertzsprung-Russell diagram. The majority of stars are on the main sequence, burning hydrogen into helium in their cores.

Main sequence turnoff point:

The point on the Hertzsprung-Russell diagram at which stars leave the main sequence and enter the red giant phase of evolution. The turnoff point is directly related to the age of the cluster.

Metallicity:

The fraction of the mass of the star in elements heavier than hydrogen and helium (known as metals).

Open cluster:

A group of stars which formed from the same molecular cloud at roughly the same time.

Parsec (pc):

Unit of length used to measure distances outside the solar system. Equal to 3.1×10^{16} m.

Photometer:

An instrument which measures the intensity of light, by collecting and counting photons.

Photon:

An individual packet of electromagnetic light.

Signal-to-noise ratio (S/N ratio):

Ratio of the number of photons from the source compared to the number of photons from unwanted interference, such as the sky background and the electronics.

Sky background:

An observation of a region of the sky containing no astronomical objects. Since an observation of an object will also include a contribution of light from the background, this must be subtracted to calibrate the observation.

Zero age main sequence (ZAMS):

The position of a star when it first enters the main sequence.