13. Exploring Starlight (Part 1 - Magnitudes, HR diagrams and distances)

Edexcel GCSE Astronomy Course

13.1 Understand the astronomical magnitude scale and how apparent magnitude relates to the brightness of stars as viewed from Earth.

Key points for understanding the astronomical magnitude scale:

1. It is a scale originally based on visual estimates by an ancient astronomer (Hipparchus).
2. The brightest stars have lowest magnitudes so 1 is a bright star and 5 is a dim star.
3. The dimmest stars visible by eye under perfect conditions are magnitude 6.
4. With binoculars this can be extended to magnitude 9.5.
5. Really bright objects have negative magnitudes e.g. Venus -4.6; full Moon -12.74.
6. Modern instrument measurements show that there is a difference of about 2.5 times in brightness between each magnitude e.g. a magnitude 6 star is therefore (2.5x2.5x2.5x2.5x2.5) or 2.5^5 or nearly 100 times dimmer than a magnitude 1 star

13.2 Understand the term absolute magnitude

- Apparent magnitude means how bright an object appears to be from Earth
- Absolute magnitude means how bright it would actually be at a standard distance from Earth
- For some really detailed information about the astronomical magnitude scale, how it came about and how to compare magnitudes, go to this website:

  https://earthsky.org/?s=astronomical+magnitude and this video gives a really good explanation too https://www.youtube.com/watch?v=9P8Veb_AIJ0&feature=emb_logo&ab_channel=EyesontheSky

- You could also go out at night to look for some well known stars and check or estimate their magnitudes with a star chart or planetarium software such as Stellarium http://stellarium.org/

  What is the dimmest star you can see with the naked eye at your observing site? What does this tell you about light pollution in your area?

Absolute and apparent magnitude exercise

- In the table below, why is Deneb's apparent magnitude from Earth larger than Merak's when Deneb is nearly 20 times further away? What other reasons could there be for Deneb having a higher luminosity? How could size affect it? How could temperature affect it?
- In the blank column, write a number from 1 for the brightest, or most luminous star, to 4 for the dimmest, or least luminous, star. Check your answers by changing the font colour in column 7.

Star	**Constellation**	**Apparent Magnitude**	**Absolute Magnitude**	**Distance from Earth (ly)**	**Relative brightness or luminosity**	**Check your answer**
Deneb	Cygnus	1.25	-6.93	1412		
Polaris	Ursa Minor	1.95	-3.66	433		
Merak	Ursa Major	2.3	0.36	80		
Shedir	Cassiopeia	2.2	-2.02	228		

13.3 Be able to use the distance modulus formula to determine the absolute (M) or apparent magnitude (m) of a star, given the distance to the star (d):

$$M = m + 5 - 5\log d$$

where d is the distance in parsec

Using this equation to convert between absolute magnitude (M) and apparent magnitude (m) is not too difficult - given M or m, just plug it in to the equation, use your calculator to work out the answer and there you go!

However, it is a strange looking equation with a couple of random looking 5’s thrown in, a log function and a strange unit called the ‘parsec’.

Let’s see how much of this we can explain and then look at a couple of examples to show you how straightforward it really is to use the equation.

(By the way, you don’t need to learn the equation, just know how to use it).

What is a parsec?

13.10 Understand that an angle of one degree (°)comprises 60 minutes of arc (arcmin) (60’) and that each arcminute is comprised of 60 seconds of arc (arcsec) (60’)
13.11 Understand the term parsec (pc) 2c, 2d
13.12 Be able to determine astronomical distances using heliocentric parallax

A parsec is a unit of distance used by astronomers.

They use it because the kilometre is insignificantly small once we want to measure distances to even the nearest stars.

They also use it because they cannot measure distances directly as they don’t have tape measures long enough to reach. Instead they measure angles, showing how far objects move across the sky. Angles can be measured very precisely in degrees, minutes (1/60 of a degree) and seconds (1/60 of a minute or 1/3600 of a degree).

To understand parsecs, we first have to understand something called parallax.

What is parallax?

This diagram gives an excellent explanation:

https://simple.wikipedia.org/wiki/Parallax#/media/File:Parallax_Example_en.svg

To make the bottom, blue square appear behind the yellow star, you would have to stand at viewpoint A, but to make the top, red square appear behind the yellow star you would have to stand at viewpoint B.

Imagine what would happen if the yellow star was nearer to the squares - yes, viewpoint A and viewpoint B would have to be further apart for the same result.

This happens with real stars - as the Earth moves through space, the nearer stars look as if they are moving relative to very distant stars. This is called parallax.

The nearer a star is, the further it appears to move across the sky.

So, what IS a parsec?

The parsec (pc) is defined like this:

One parsec corresponds to the distance at which the mean radius of the earth's orbit makes an angle of one second of arc against the distant, background stars.

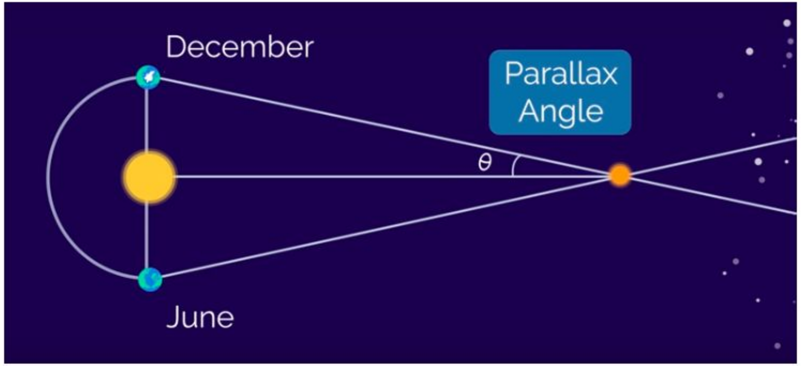
So, if a star was at one parsec from Earth it would appear to move by 2 seconds (2”) across the sky between an observation on June 21st and an observation on December 21st as the Earth has moved by one whole diameter of its orbit across the sky.

Here’s a very clear diagram explaining this from this website which also has videos and more detailed explanations of parsecs:
https://earthsky.org/space/what-is-a-parsec

As a distance, 1pc = 3.26 light years,

3.086×10^{13} kilometres

Or 206,265 **AU**



One parsec is the distance to an object whose parallax angle is one arcsecond. The radius of the Earth's orbit equals one astronomical unit (AU), so an object that is one parsec distant is 206,265 AU (or 3.26 light-years) away.

Back to the equation:

$$M = m + 5 - 5\log d$$

It is still a strange equation, so if you are the kind of person who needs to know where equations come from, try this site: https://astronomy.swin.edu.au/cosmos/D/Distance+Modulus

Otherwise, just a few facts that might help to explain it:

- The 'log' part is there because magnitudes do not change in the way you would expect. Magnitude 1 stars are not twice as bright as Magnitude 2, but about 2.5 times brighter - this means Magnitude 1 stars are nearly 100 times brighter than Magnitude 6 stars. This is called a 'logarithmic scale'.
- The standard distance used to define absolute magnitude is 10pc, which means that a star's absolute magnitude is how bright it would look at 10pc from Earth.
- The 5's come about from algebra involving log(10) and 2.5 !

It's probably best just to try out some examples to see how it works:

Examples using the distance modulus equation:

Try these examples, with answers, from the Las Cumbres Observatory:

https://lco.global/spacebook/distance/calculations-and-questions-based-distance-modulus/

If you need extra help after trying these, watch this video showing model answers being written out:

VIDEO

13.5 Understand how stars can be classified according to spectral type
13.6 Understand how a star’s colour and spectral type are related to its surface temperature

Write answers these questions about stars from the link that follows:

1. What are stars?
2. Which force holds stars together?
3. Where does nuclear fusion take place?
4. What is a more scientific word for ‘glowing’?

https://www.schoolsobservatory.org/learn/astro/stars

Find answers to these questions about spectral type from the link that follows:

1. What are the letters used for the seven spectral types of stars?
2. Who invented this classification system?
3. Give two differences between O and M class stars.

https://www.schoolsobservatory.org/learn/astro/stars/class

13.4 Understand what information can be obtained from a stellar spectrum, including **a. chemical composition** b. temperature c. radial velocity

A stellar spectrum is produced when the light from a star is collected by a telescope and then split into its individual colours by an instrument called a spectrometer.

This is similar to the spectrum of colours you may have seen produced by a prism but each class of star produces a slightly different spectrum so that astrophysicists can use these to identify a star's class like a forensic scientist would use a fingerprint - here are some example spectra so you can see how this would work:

https://people.highline.edu/iglozman/classes/astronotes/media/spec_class.jpg

So you can already see that different chemical composition is one reason for differences in the spectra of different stars.

13.4 Understand what information can be obtained from a stellar spectrum, including a. chemical composition **b. temperature** c. radial velocity

The colour of a star depends on how hot its surface temperature is.

Blue-green stars are hottest and orange-red stars are coolest - our Sun is yellow and so has a mid-range temperature.

This link shows a list of colours and temperatures of stars:

http://naasbeginners.co.uk/AbsoluteBeginners/Star_Colours.htm

This site has a beautiful image of 25 different stars - try estimating their temperatures from their colours:

https://nightskypix.com/star-colors/

13.4 Understand what information can be obtained from a stellar spectrum, including a. chemical composition **b. temperature** c. radial velocity

Why does a star's colour depend on its temperature? The video linked at the bottom of the page will answer all these questions about the colour of stars - stop it at the times shown and write down the answers.

1. Approximately how long after the Big Bang can stars and galaxies be seen? (16s)
2. What were the four colours stars were first categorised into by astronomers? (40s)
3. What was used to break up these colour classes? (48s)
4. What characteristic of a star made more sense for categorizing them? (1:00)
5. What is the approximate temperature of the hottest stars? (1:10)
6. What is the approximate temperature of the coolest stars? (1:12)
7. How many classes are stars now categorized into? (1:19)
8. Who invented this Harvard System for classifying stars? (1:26)
9. Fill in the blanks with upper case letters to complete this gender non-specific star class mnemonic: _h _e A _ine _oat _ick _e (1:52)
10. Whose law relates the temperature of an object to the peak wavelength of electromagnetic waves that it emits? (2:01)
11. Pause the video at 2:05min and use the graph shown to complete this table on the next page

https://www.youtube.com/watch?v=Y5VU3Mp6abI

Complete the table using information from the graph shown in the video at 2:05min:

Temperature of star (K)	Peak Wavelength of light emitted (nm)	Dominant Colour of Spectrum
5500	505	Green
5000		
4500	525	Orange
4000		
3500		Dark Red

Describe what happens to the peak wavelength as the temperature gets lower - does it get longer or shorter?

13.4 Understand what information can be obtained from a stellar spectrum, including a. chemical composition b. temperature **c. radial velocity**

You may already know about redshift. This happens when stars or galaxies are moving away from Earth making the wavelength of the light they emit get longer, or shift towards the red end of the visible light spectrum.

Blueshift is the opposite, where the wavelengths get shorter because the start or galaxy is moving towards the Earth.

This is very useful when detecting exoplanets - planets around other stars. An orbiting planet will make a star move in a small circle as shown in this short NASA video - when the star is moving away you will see the wavelength of light it emits getting longer and redder. When the star moves towards you the wavelength gets shorter and bluer. If this colour shift is detected it can tell astrophysicists that there may be a planet orbiting the star:

https://www.youtube.com/watch?v=WK0WAmiP_Dk&ab_channel=NASAVideo

13.8 Understand how a star's life cycle relates to its position on the Hertzsprung-Russell diagram, for stars similar in mass to the Sun and those with masses that are much greater

Using the same video you watched before, carry on past 2:05min and stop the video at the times shown to answer these questions:

1. What is the name of the diagram astrophysicists use to classify all the information on stars? (3:44)
2. Where do the majority of stars lie on this diagram? (4:08)
3. Which type of stars are cool but luminous? (4:21)
4. Which type of stars are hot but dim? (4:25)
5. Which two characteristics of stars can be inferred from the vertical and horizontal axes of the diagram? (4:38-4:46)
6. Which types of stars deviate from the trend of the Main Sequence? (4:57)
7. Which inward force gets larger in larger stars? (7:22) (Ouch - pushing is not a good word!)
8. What has to increase to counteract this force to prevent the star collapsing? (5:33)
9. Which type of nuclear reaction transfers the energy to provide this outward pressure? (Not in then video - think back to previous lessons)
10. How much more mass do blue stars have compared to the Sun? (5:48)
11. What is the mass of a cool, dim, red star compared to the Sun? (5:55)

https://www.youtube.com/watch?v=Y5VU3Mp6abI

There is a summary of HR diagrams here https://www.schoolsobservatory.org/learn/astro/stars/class/hrdiagram

13.7 Be able to sketch a simple Hertzsprung-Russell diagram, including labelled axes and indicate the positions of the following:
a main sequence stars b the Sun c red and blue giant stars d white dwarf stars e supergiant stars

This link shows a picture of a full Hertzsprung-Russell (HR) diagram with thousands of known stars plotted on it according to their luminosity/absolute magnitude on the vertical axis and temperature/spectral type/colour on the horizontal axis. You will see that stars tend to group into certain types on the diagram e.g. main sequence, supergiants, white dwarves etc.

https://en.wikipedia.org/wiki/File:HRDiagram.png

You should be able to sketch a simplified version of this, such as the one shown here - learn and practise sketching this, checking your sketches each time to see if they are correct:

https://glhsastronomy.files.wordpress.com/2014/02/hr-diagramunits.jpg

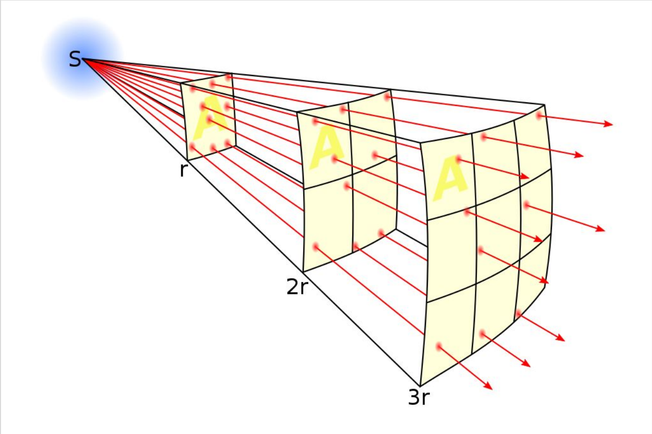
The Sun is in the centre of this diagram because it shows luminosity as a ratio to the luminosity of the Sun which is equal to 1 for the Sun itself!

13.9 Understand the inverse square relationship between distance and brightness/intensity

Light from a single point spreads in all directions in a spherical shape - it would look like a bubble expanding if we could watch quickly enough.

The surface area of a sphere is $A = 4 \pi R^2$ where R is the radius of the sphere.

A star's luminosity, L, measures the energy it emits as light, which then gets spread over the area A as the bubble, or sphere, grows. This diagram shows the consequence of this - if radius doubles from r to 2r then the original light will be spread over four times as much area and if radius trebles to 3r it will be spread over nine times as much area and so on:



Go to the next slide to test your understanding of this law and to see how it can be used to find the distance to a star.

Using the inverse square law:

Test your understanding of the inverse square law with this quiz - just remember, if distance doubles intensity decreases by a quarter because $1 / (2^2) = ¼$
https://imagine.gsfc.nasa.gov/features/yba/M31_velocity/lightcurve/quiz.html

Full, written answers can be found here when you have tried the quiz:
https://www.abingdonsciencepartnership.org/gcse-astronomy/ (under Topic 13)

If the Earth is a distance d from a star, then the star's light will be spread over a sphere of area $A = 4 \pi d^2$ once it reaches Earth - this is called its intensity, I, so

$$I = L/(4 \pi d^2) \text{ or } d = \sqrt{(L / 4 \pi I)}$$

So, if we know a star's original luminosity, L, and we measure the intensity of its light at Earth, I, we can use this equation to calculate its distance, d. First though, we need to know how to find L, so read on...

13.13 Understand how to use a Hertzsprung-Russell diagram to determine distances to stars

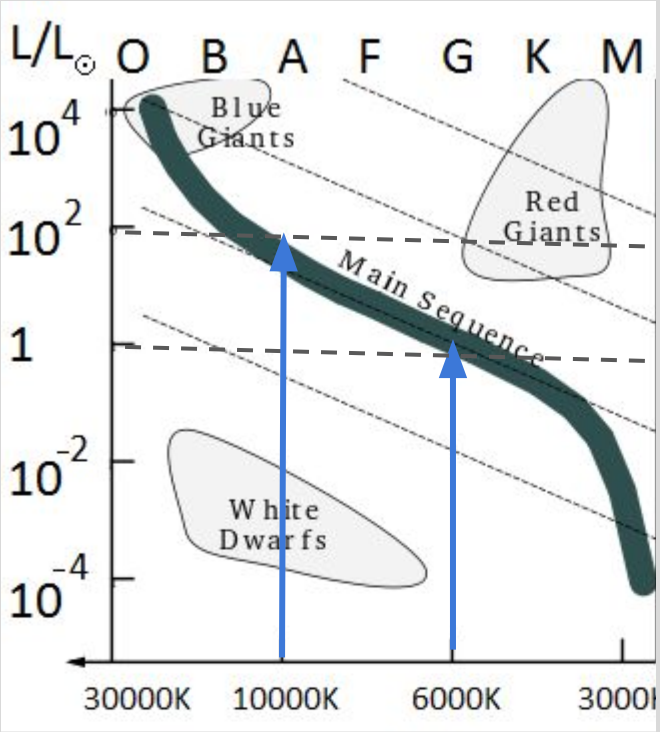
To use the inverse square law to calculate the distance to a star, we need to know two things - it's luminosity and the intensity of its light measured on Earth.

We can use the HR diagram to estimate its luminosity. For example, in this simple HR diagram a G class star with a surface temperature of 6000K would lie on the Main Sequence and have a relative luminosity $L/L_{\odot}=1$ meaning that its luminosity would be the same as our Sun, a yellow dwarf star.

An A class star with a surface temperature of 10000K would be 10^2 or 100 times more luminous than our Sun.

So we can find luminosity, L, from a HR diagram, measure intensity, I, on Earth and use

$I = L/(4 \pi d^2)$ or $d = \sqrt{(L / 4 \pi I)}$ to find distance d. Clever!



Example based on Edexcel GCSE questions:

a. Complete the labels on the horizontal axis by filling in the missing spectral types.

b. **U**se the diagram to estimate a mean value for the absolute magnitude, M, of an F class star.

c. Use the following equation to calculate the apparent magnitude, m, of this F class star at 100pc from Earth

$$M = m + 5 - 5\log d$$

d. Calculate the value of d in m if 1 pc = 3×10^{16}m

e. Given that the absolute magnitude of the Sun is approximately 5; that the Sun's luminosity is 4×10^{26} Watts and each order of magnitude difference is equal to a difference of 2.5 in luminosity, calculate the luminosity of this star.

f. Calculate the intensity of this star's light measured on Earth using the equation

$$I = L/(4 \pi d^2)$$

g. Give the correct units for intensity, I

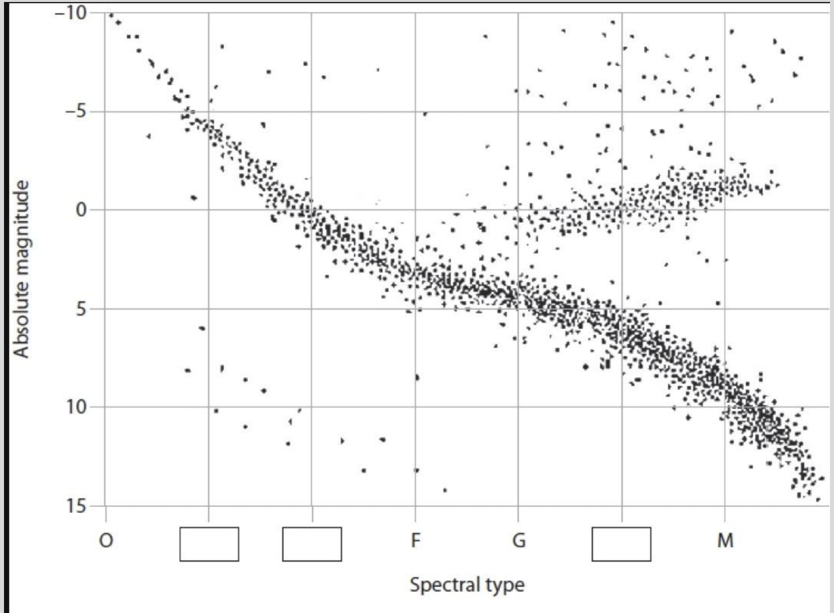


Figure 4

Model answers:

a. B A K

b. M = 3 (see diagram)

c. $M = m + 5 - 5\log d$

$3 = m + 5 - 5\log(100) = m + 5 - (5x2)$

$3 = m - 5$ so $m = 8$ (too dim for naked eye)

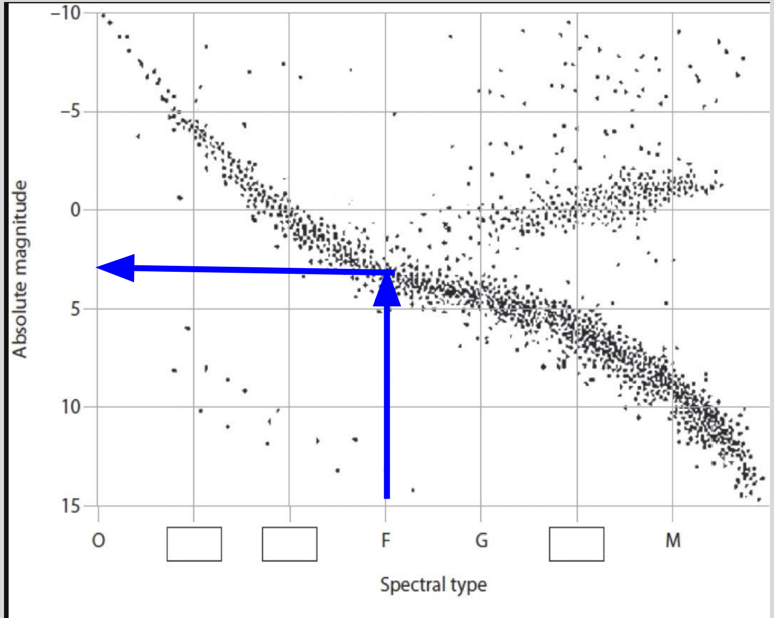


Figure 4

d. $100pc = 100 \times 3x10^{16}m = 3 \times 10^{18}$ m

e. Difference in M = 5-3 = 2 magnitudes, each magnitude = 2.5 times brighter so L for this star is $2.5 \times 2.5 \times 4x10^{26} = 25x10^{26}W$

f. $I = L/(4\pi d^2) = 25x10^{26} / (4\pi (3x10^{18})^2) = 2.2x10^{-11}$

g. Watts per square metre ($W\ m^{-2}$)