1. Our understanding of celestial objects depends upon observations made from Earth or from space near the Earth.

- discuss Galileo's use of the telescope to identify features of the Moon

Galileo Galilei produced a telescope after hearing of the concept by grinding lenses to use as the required optics. This allowed for magnification and after many attempts, he had 30x magnification refracting telescope that produced an upright image.

When observing the moon, he found that its surface had defining dark spots that changed with the angle of solar illumination. He reasoned these spots were shadows of the moon's surface which was not smooth or uniform, but uneven and rough with cavities and prominences. Instead, he saw the moon as having mountains and valleys.

He was also able to calculate the height of mountains on the moon using measurement of the length of their shadows, estimating them to be several kilometres high.

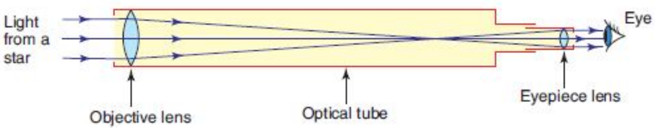
Further discoveries such as the moons of Jupiter also challenged the Aristotelian view supported by the Church.

The impact of the telescope on astronomy was big, and these discoveries were only due to the first application of a telescope. As technology improved, building larger and better telescopes allowed further discoveries and even better science.

Telescopes

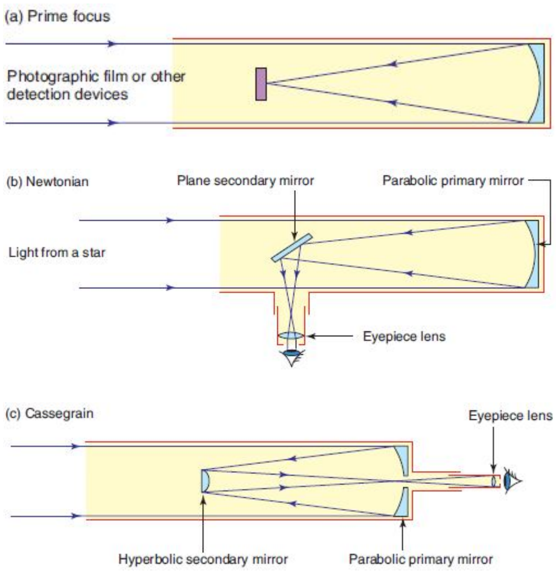
Refracting Telescopes

These are telescopes such that light enters one end and form s the image at the other. Two lenses, (objective and eyepiece) focus the image, but the image is seen upside down and back to front. Although this isn't a problem when observing stars.



Reflecting telescopes

This type has a parabolic concave mirror, gathering and focusing starlight by reflection of the rays. There are many variations as illustrated:



The most basic design is the prime focus, used especially for radio telescopes such that the signal is detected electronically.

Small scale optical telescopes, such as those in high schools, tend to use the Newtonian reflector design.

However, larger research telescopes utilise the Cassegrain design, directing light through a hole in the primary mirror. This design can be produced relatively cheaper than similarly sized refracting telescopes.

define the terms 'resolution' and 'sensitivity' of telescopes

There are three measures of telescope performance, magnification, resolution and sensitivity.

Magnification

This is in fact the least important and is given by the formula:

$$m = \frac{f}{f_e}.$$

Where f is the focal length of the telescope itself (objective lens in simple refractor, or primary mirror in simple reflector) and F_e is focal length of telescope eyepiece.

i.e. f=1.25m, f_e=0.0125m, m=1.25m/0.0125m=100x magnification.

Sensitivity

This is the light gathering power of the telescope, i.e. its ability to pick up faint objects or observation. The sensitivity depends on the collecting area of the lens or mirror. A larger diameter telescope allows more light to be gathered and focused when forming an image since collecting area is greater.

The quality of optics also influences the level of sensitivity.

A telescope with mirror 7 times the diameter of another is 49 times more sensitive.

Theoretical Resolution

This is the ability for a telescope to distinguish two close objects as separate images and is measured as an angle. The smaller the angle, the higher the resolution. It depends on the wavelength of the EM radiation being collected (i.e. light) and also the diameter of the telescope. Dawes limit describes this mathematically:

$$R = \frac{2.1 \times 10^5 \lambda}{D}$$

R = resolution (arcseconds), λ = wavelength (m), D = diameter (m)

The theoretical resolution of a 64m telescope observing radio waves of wavelength 3cm is:
R=[(2.1x10^5)(0.03)]/64 = 98arcsec

Theoretical resolution of 3.9m Anglo-Australian Telescope observing starlight wavelength 500nm is:
R=[(2.1x10^5)x(500x10^{-9})]/3.9 = 0.027arcsec

It's seen that by nature of the wavelength, radio telescopes have lower resolution than a optical telescope of comparable diameter.

identify data sources, plan, choose equipment or resources for, and perform an investigation to demonstrate why it is desirable for telescopes to have a large diameter objective lens or mirror in terms of both sensitivity and resolution

To demonstrate the light gathering ability of different lenses, a few biconvex lenses of different diameter were used. A light meter was placed in the sunlight, and two polarising filters are placed perpendicularly to block out all light. Now the top filter is rotated such that the meter produces a zero reading.

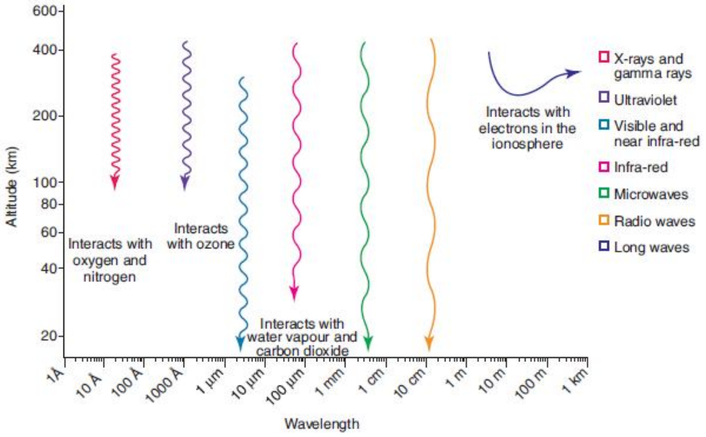
Using the smallest lens, its diameter is measured, and area calculated. Lens gathers the sun's light onto the panel, but the light is not focused onto a point, but rather a circle of light filling the panel of the light meter. Record reading from light meter.

This method is repeated with lens of different diameter in ascending order.

It can be said that the reading on the light meter increased as the diameter of the lens increased. This implicates that it is desirable for telescopes to have large diameter objective lens or mirror to improve its sensitivity.

discuss why some wavebands can be more easily detected from space

Although all the various components of EM wavelengths impinge upon the upper atmosphere, atmosphere prevents most components of the electromagnetic spectrum from penetrating to the ground. Only visible light, radio waves, and some UV and IR make it to the ground, the rest is absorbed by the atmosphere at varying altitudes.



EM SPECTRUM	WAVELENGTH (m)	COMMENT
Gamma rays	$< 10^{-10}$	Absorbed by the atmosphere.
X-rays	10^{-11} to 10^{-7}	Absorbed by the atmosphere.
Ultraviolet	10^{-8} to 4×10^{-7}	Mostly absorbed by the atmosphere.
Visible light	4×10^{-7} to 7×10^{-7}	Not absorbed by the atmosphere.
Infra-red	7×10^{-7} to 1×10^{-2}	Freely penetrates haze but is incompletely absorbed by the atmosphere.
Radio waves	1×10^{-3} to 1×10^{6}	A broad grouping of microwaves and radio bands — uhf, vhf, hf, mf and lf. Not absorbed by the atmosphere.

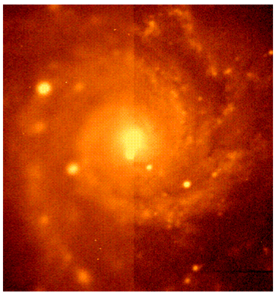
Note Gamma Rays and x-rays ionise molecules in the atmosphere, therefore absorbed.
Hence, ground based telescopes can only effectively operate in the visible spectrum (optical telescopes, Anglo-Australian telescope) and radio bands (radio telescopes, Parkes).

Other frequencies can only be absorbed at higher altitudes, (plane, balloon), or in space (satellite - Hubble). In space, without absorption by the atmosphere, most wavebands can be detected.

- Gamma rays - Compton Gamma Ray Observatory
- X-trays - Chandra X-ray telescope

In space, seeing effects are also minimised due to lack of atmosphere, and the visible spectrum can also be observed easier.

discuss the problems associated with ground-based astronomy in terms of resolution and absorption of radiation and atmospheric distortion



LHS - Seeing
RHS - Clearer processed side.

Firstly, ground based astronomy is limited to certain wavebands of the EM spectrum (light/radio) due to absorption of radiation.

- Gamma and x-rays ionise molecules in the atmosphere and are strongly absorbed.
- UV radiation is mostly absorbed by the ozone layer.
- Infrared wavelengths incompletely absorbed by water vapour and carbon dioxide.
- Long radio waves are reflected by the ionosphere.

The very low intensity of these wavelengths that reach the ground means sensitivity of ground-based astronomy of these wavelengths is decreased.

Therefore, ground-based astronomy is generally restricted to visible and radio waves which do penetrate the atmosphere. However, since different wavelengths are absorbed to different extents, the true colour of the image taken by ground optical telescopes is distorted.

Ground-based astronomy is also affected by 'seeing', the turbulent air of the atmosphere varies in temperature and pressure which constantly alter the refractive index of light, distorts path of starlight through it (making it twinkle). This blurs a star and lowers practical resolution to about 1 arcsec despite large ground-based telescopes having higher theoretical resolutions (But the larger diameter collecting area does provide greater sensitivity.) The best locations, i.e. Mauna Kea, have seeing of about 0.5 arcsec.

Scattering due to suspended dust particles or molecules of O_2 and N_2 in the atmosphere also reduce the intensity of light from astronomical sources.

Radio telescopes are not affected much by seeing or scattering due to the longer wavelengths being observed. Unlike visible wavelengths, they are much longer and not affected by water vapours and oxygen in the atmosphere, or rain.

Finally, the sun is also another obstacle, restricting optical astronomers to night viewing, and creates interference for radio astronomers (preventing radio telescope operation within 90° of the Sun). *Although the sun is a problem for satellite telescopes as well.*

outline methods by which the resolution and/or sensitivity of ground-based systems can be improved, including:
- adaptive optics
- interferometry
- active optics

Radio telescopes are quite sensitive, and are not affected by 'seeing' (twinkling) effects, but have poor resolution. Optical telescopes are limited by seeing, limiting their effective resolution to be no better than a 200mm telescope (only sensitivity is better). Solutions can be:

- Place optical telescopes on mountaintops to get above the denser atmosphere in order to reduce atmospheric distortion and get away from light pollution. This improves resolution and allows it to operate near its theoretical resolution.
- Superior lens technology and coating can improve reflectivity to increase sensitivity.

However, modern technology also helps to improve ground based telescopes and improve resolution and sensitivity.

Interferometry

Radio telescopes have poor resolution due to the long wavelength being observed. $R=(2.1\times10^5\lambda)/D$.

Although **resolution can be improved** by increasing diameter of the dish, it is expensive to produce very large radio telescopes.

Interferometry is usually done for ground based radio telescopes, involving a cluster of many radio telescopes to be laid out in an array. Each telescope observes wavefronts of the same celestial object and data from each element of the array is combined to form an interference pattern. Computers mathematically analyse the interference patterns to reveal information about the structure of the radio source.

The effective angular resolution of such an array is equivalent to that of a single dish having a diameter equal to the baseline (largest distance between two telescopes). However, sensitivity is still proportional to the light collecting area of all the dishes, still **better sensitivity** than only one dish.

Setups, such as the Very Large Array (VLA) combine signals of 27 radio dishes set up in a Y pattern, behaving as a single radio telescope with a diameter of 36km across, providing a resolution of a dish of 36km, and sensitivity of a dish 130m in diameter.

The Very Long Baseline Array (VLBA) consists of ten 25 m dish at locations between Hawaii and the Caribbean, providing resolution of 0.001 arcsec.

Images from large optical telescopes can also corrected using interferometry techniques.

Active Optics

The larger the primary mirror, the bigger the collecting area and hence the better sensitivity. However, they distort with changes in temperature and telescope orientation, and for many years, this placed a limit on mirror size.

Active optics is a slow feedback system used to correct sagging or other deformities in the primary mirror of large modern reflector telescopes. This **improves sensitivity** by allowing modern telescopes to have larger mirrors (up to 8-10m diameter).

Active optics work by a wavefront sensor slowly sampling the light leaving the primary mirror to detect alterations in incoming light due to deformities in the primary mirror. Since alterations due to atmospheric effects (i.e. seeing) occur on smaller time scales, slower sampling ensures that detected changes are only due to mirror distortions (sampling once every half or one second).

This information is processed by a computer which calculates optimal mirror shape to correct distortions and computes the required shape adjustments. Corrections are sent to actuators at the back of the mirror that can push or pull the mirror back into its correct shape. Therefore, deformities in mirror shape is corrected, preventing mirror distortion to produce a clearer image, **improving resolution**.

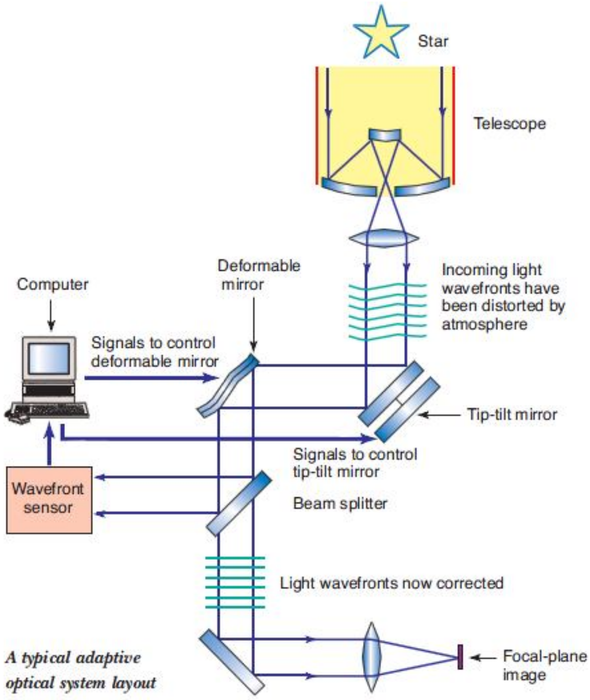
The Keck I&II uses this system, the position and curvature of each piece is controlled by the active system and is adjusted twice per second. Their mirrors are very thin, large and segmented.

Adaptive Optics

Adaptive optics is a fast feedback system operating on a much faster time scale that attempts to correct 'seeing' effects due to atmospheric turbulence, rather than mirror distortions, **improving resolution**.

A wavefront sensor is placed between the primary mirror and the lens, and distortion due to atmospheric turbulence is sampled up to 1000 times a second and corrections are computer-calculated.

Since so many corrections are occurring in one second, the primary mirror is usually too heavy to move at such speeds, hence corrections are sent to one or two secondary mirrors to straighten the image. Detection and correction must occur much faster than changes in atmospheric distortion for adaptive optics to be successful.



A typical adaptive optical system layout

Possible secondary mirrors can be:

- A 'tip-tilt' mirror which makes small rotations to adjust for slight changes in the position of light (Anglo-Australian Telescope).
- A deliberately deformable secondary mirror adjusting for deformities in the light to make images sharp.

However, adaptive optics only works when a reference star of sufficient luminosity is found near the object of observation. The further from the reference star, the more image quality degrades (thus adaptive optics provides a small field of view. Although, an alternative is to direct a laser beam into the atmosphere as a reference light source, detecting backscatter from altitudes 15-25km.

Implementation of adaptive optics in larger telescopes is still in process there are considerable technological challenges.

2. Careful measurement of a celestial object's position in the sky (astrometry) may be used to determine its distance.

Apparent position changes of a body can be measured to a high order of accuracy using positional astronomy (i.e. astrometry). These apparent position changes are due to real motion of the body, or the Earth's motion around the orbit, resulting in a shifting point of observation.

- define the terms parallax, parsec, light-year

An arcsec is 1/60 of an arcminute, which is 1/60 of a degree.
Therefore, an arcsec is 1/3600 of a degree
The closer the star, the greater the annual parallax, i.e. Proxima Centauri with 0.772"

Parallax is the apparent change in position of an object due to a shift in the observer's point of observation.

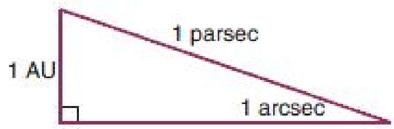


Figure 15.4 When $p = 1$ arcsec, then $d = 1$ parsec.

A parsec is the distance from the Earth to a point that has an annual parallax of one arcsec, i.e. the distance from which, the Earth's distance from the Sun would subtend one arcsec. *A parsec is favourable to use as it doesn't depend on an arbitrary time scale, as the light year; aka parallax second.*

A parsec is about 30.857×10^{12}km, or 206265 AU or 3.2616 light years.

A light year is the distance that light or other EM waves travel through vacuum in one year. It is 9.4605×10^{12}km or 0.3066 parsecs.

- explain how trigonometric parallax can be used to determine the distance to stars

Limitation: If the star is too far away, the parallax may be too small to be calculated correctly

If drawing the picture, include 1AU on both top and bottom sides, indicate right angle, label [Earth i.e. Jan] (and Earth 6 months later, i.e. July). Label background stars, and draw arrow from one apparent position to another and label **"apparent shift against background stars."**

Although parallax can be immediately used to determine distances, in reality:

- *The angle is always <1.0arcsec, so careful observation and precision is required.*
- *Ground based measurements must have corrections for atmospheric refraction and 'seeing'*
- *The greatest baseline (Jan and July) is 2AU by observing the star 6 months*

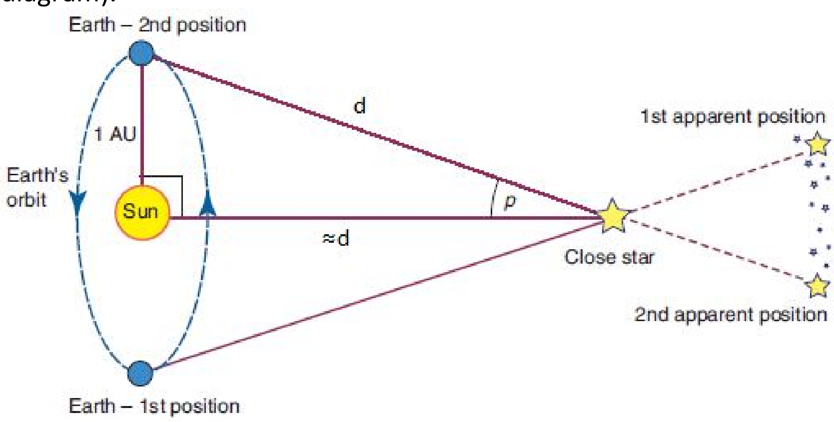
Parallax is the apparent shift in an object due to a change in the observer's position. An appreciable parallax for stars requires a large change in the observer's position.

A star's annual parallax (p) is half the angle through which the star appears to shift against the background of more distant stars as the Earth moves from one side to the other in its orbit. More precisely, the star annually traces out a parallactic ellipse and the annual parallax is the angle subtended by the ellipse's semi-major axis.

The star's shift can be measured by taking photographs at 6 month intervals from opposite ends of the Earth's orbit.

Trigonometric parallax uses trigonometry to solve the triangle formed to directly determine distances.

Hence, an isosceles triangle is formed with the diameter of the Earth's orbit as the baseline, and the distance from the sun to the star as the perpendicular height (draw diagram).



The annual parallax is the semi-vertical angle, and so the distance of the star from Earth is determined by:

$$\text{Distance of star from Earth} = \frac{\text{radius of Earth's orbit}}{\sin p}$$

But at small angles, the approximation is as follows: $\sin\Theta = \tan\Theta = \Theta$

- *The greatest baseline (Jan and July) is 2AU by observing the star 6 months apart.*

$$\text{Distance of star from Earth} = \frac{\text{radius of Earth's orbit}}{\sin p}$$

But at small angles, the approximation is as follows: sinϴ = tanϴ = ϴ

And since the baseline is the radius of orbit, this length is taken as **1AU**.

Hence, the above formula for distance of a star from Earth can be stated as:

$$d = \frac{1}{p} \qquad d = \text{distance from Earth (parsecs, pc)} \quad p = \text{parallax (arcsec)}.$$

Due to this relationship, **stars closer to us have a larger angle of parallax** than stars further away.

However, since parallax measurements are often very small, only the parallax of relatively closer stars can be taken before the error is greater than the angle being measured. Hence, distances to relatively nearby stars can be calculated accurately, and more distant stars can be determined using techniques which use nearby stars as reference stars.

solve problems and analyse information to calculate the distance to a star given its trigonometric parallax using:

$$d = \frac{1}{p}$$

d is in parsecs (pc), while p must be in arc seconds ("). If in milli-arcsec or other unit, must be converted to arcsec.

Note significant figures. Though the 1AU isn't taken in consideration or else all calculation would be 1sf.

Determine the distance, in parsecs and light years, of Procyon with an annual parallax of 0.286 arc seconds.

d = 1/p
= 1/0.286
= 3.50 pc
or = 3.50x3.26 = 11.4 light years (3sf)

Given the diagram of the night sky, and measuring parallax using ruler, note that if the linear change of X units which corresponds to a change of Y arcsec, then Y **must be divided by 2 as it is half the angle through which the star moves**. This is the definition of the parallax.

discuss the limitations of trigonometric parallax measurements

HIPPARCOS measures parallax from above the atmosphere.
<See next dot point>

Parallax angles taken from stars are extremely small as even the largest parallax, from Proxima Centauri, is only 0.772 arcsec.

Traditionally, measurement of trigonometric parallax is made photographically using large ground-based optical telescopes. However, atmospheric distortions (seeing) makes the smallest parallax measurable from the ground to be approximately 0.01 arcsec. This corresponds with a maximum accurately measurable distance of 100 parsecs, which is a very short distance in astronomical terms. Beyond 100 parsecs, the parallax angle is so small that errors in measurement become almost as big as the angle being measured.

A telescope in space places it above the atmosphere, removing atmospheric distortion (seeing). Additionally, space telescopes can observe shorter wavelengths of radiation from stars which effectively increases resolving power, allowing measurement of smaller parallax. Hence, the only limitations of trigonometric parallax measurements is the quality of optics and size of telescope objective.

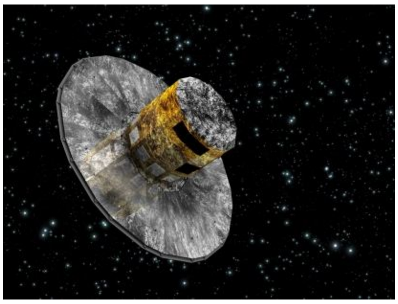
Finally, using a larger baseline would increase the annual parallax of celestial objects (i.e. orbit around the sun with Mars' orbit radius). This allows for more accurate measurement and can be used to determine distances for more distant stars.

gather and process information to determine the relative limits to

Due to atmospheric distortion (seeing), ground based telescopes can make trigonometric parallax measurements that are at best 0.01 arcsec, which gather and process information to determine the relative limits to trigonometric parallax distance determinations using recent ground-based and space-based telescopes

Due to atmospheric distortion (seeing), ground based telescopes can make trigonometric parallax measurements that are at best 0.01 arcsec, which corresponds to a maximum accurately measurable distance of 100 parsecs. This is very short in astronomical terms, and stars beyond this cannot be measured accurately as the error of parallax measurement becomes greater than the angle being measured.

Observations from the space using satellites eliminates atmospheric blurring or seeing as it gets above the atmosphere. The ESA placed HIPPARCOS into orbit, equipped with a 290mm telescope. Between 1989-1993, it took parallax measurements of approximately 120000 stars to the precision of 0.001 arcsec using a 290mm optical telescope, 10 times more precise than the best ground based measurements, extending the maximum accurately measurable distance to 1000 parsecs.



GAIA is to be placed in the Lagrange point L2 to provide the spacecraft with thermal stability.

A next generation satellite, GAIA is planned for launch in 2012, placed 1.5 million km further out from Earth's orbit. The larger baseline increases the annual parallax of celestial bodies, allowing for more accurate measurements. Improvements in optics and technology means it can measure trigonometric parallax of stars to a precision of 10 microarcsec, which is 100 times more precise than HIPPARCOS. This allows the distances of over 1 billion stars to be determined with reasonable accuracy (10-20%), and approximately 1% of stars in our galaxy can be logged.

3. Spectroscopy is a vital tool for astronomers and provides a wealth of information

- account for the production of emission and absorption spectra and compare these with a continuous blackbody spectrum

Description of detection
In either:

1. Light from a gas at low pressure when excited
2. Or a continuous spectra passing through a cool, non-luminous gas

These can be passed through a slit, and directed through a prism or spectroscope.

This disperses the light beam into its component wavelengths and reveals the emission and absorption spectra.

When a continuous spectra is passed through, a continuous distribution of wavelengths is seen.

In spectroscopy, we study the component wavelengths of the incoming light to draw inferences about the material which produced it. For instance:

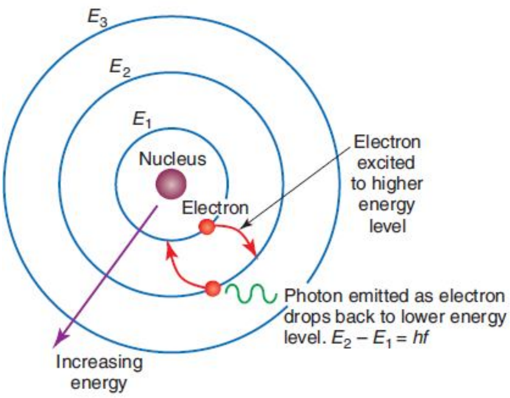
- A yellow flame when a bunsen is sprayed with sodium chloride solution
- Yellow light from the sun
- Yellow light from a torch covered with yellow cellophane

Emission Spectra

When energy (in the form of electricity or heat) is supplied to a gas at low pressure, it is absorbed by the atoms, electrons are excited and jump up to a higher energy level. When the electron jumps down and falls to a lower energy level, it releases a photon of energy corresponding to the energy drop: $E_2 - E_1 = hf$. *[E_2 - Excited State, E_1 - Ground state.*

Many such electron transitions are possible in one element and are unique to that element. Therefore, every element produces **an emission spectrum consisting of radiation at a few discreet wavelengths as bright lines against a dark background**. These bright lines correspond to each energy transition and as they are unique to each element (fingerprint of that element), spectroscopic analysis of the emission spectrum of an unknown mix of elements determines the elements present.

Note that certain transitions are more favoured (i.e. more probable, hence emission spectral line of greater intensity).



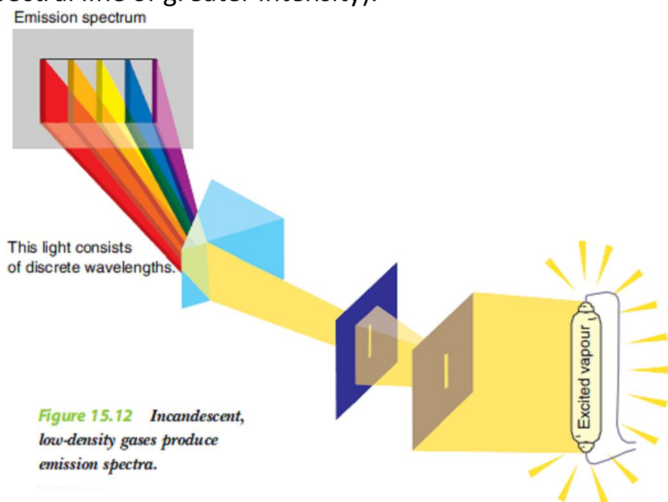


Figure 15.12 ***Incandescent, low-density gases produce emission spectra.***

Absorption Spectra

When a continuous spectra of light is passed through a cloud of cool, non-luminous gas, atoms of the gas absorb photons corresponding to the precise energy difference between energy levels within the atoms: $E_2 - E_1 = hf$. These possible transitions of electrons to higher energy levels means the gas of a certain element absorbs certain frequencies of light.

However, when an excited electron drop back to their ground state a photon of energy corresponding to the energy drop is released. And this occurs for the many electron transitions possible, essentially re-emitting the absorbed photons in all directions, reducing absorbed wavelengths in intensity.

Hence, **the absorption spectrum appears as a continuous background of colour with dark lines of discreet gaps at particular wavelengths unique to the element.**

The relative darkness of each line depends on the composition of the gas.

The wavelengths absorbed is identical to the wavelengths emitted if that gas were excited.

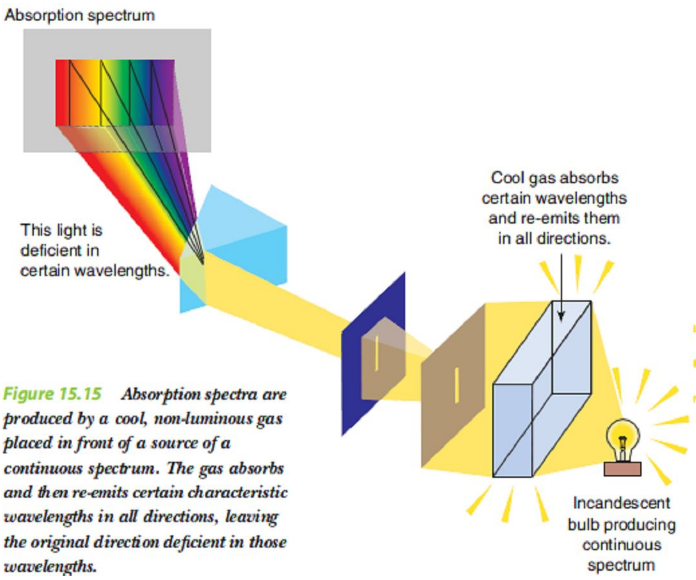


Figure 15.15 *Absorption spectra are produced by a cool, non-luminous gas placed in front of a source of a continuous spectrum. The gas absorbs and then re-emits certain characteristic wavelengths in all directions, leaving the original direction deficient in those wavelengths.*

Continuous spectra

A continuous spectrum is essentially one emitted by a black body with a continuous range of frequencies. All frequencies of EM radiation are emitted, although at different intensity.

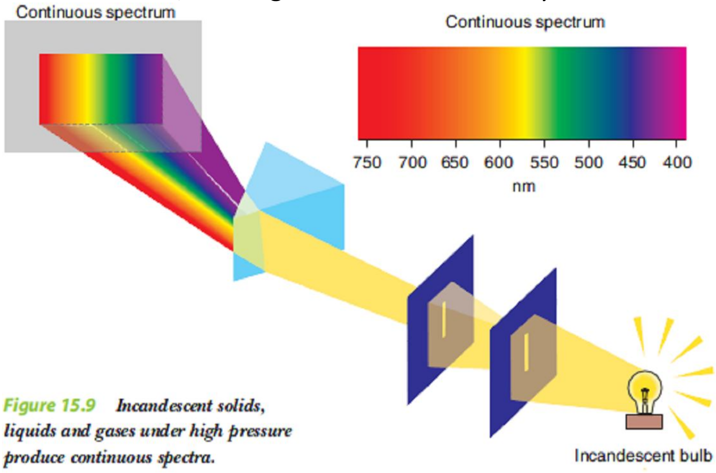


Figure 15.9 *Incandescent solids, liquids and gases under high pressure produce continuous spectra.*

This type of spectrum can be produced by a hot solid, liquid or high-pressure gas, and its output can be modelled by a black body:

- This is because radiation from an ideal black body is a continuous distribution of wavelengths.
- The intensity varies smoothly with wavelength The wavelength of peak intensity increases with temperature given by Wien's law.
- As temperature increases, the black body radiation curve becomes higher, indicating the intensity of total radiation being emitted increases.
  - This can be expressed as Stephan's Law: $L = 4\pi R^2\sigma T^4$
    - L = Luminosity (Js^{-1} or W), T= Temperature (K), R = Radius of star (m)
    - σ = Stephan's constant = 5.6705×10^{-8} $Wm^{-2}K^{-4}$
  - Hence, even if two black bodies have the same temperature, their output can vary due to the radius of the black body.

Since stars are very similar to ideal black bodies, their surface temperature can be determined by observing the dominant wavelength (wavelength of maximum intensity) by using a spectrophotometer.

Summary

Type of spectrum	Generally produced by	Celestially produced by
Emission	Incandescent low-density gases	Emission nebulae, quasars
Absorption	Cool gases in front of continuous spectrum	Atmosphere of stars
Continuous	Hot solids, liquids, gases under pressure	Galaxies, inner layers of stars

- describe the technology needed to measure astronomical spectra

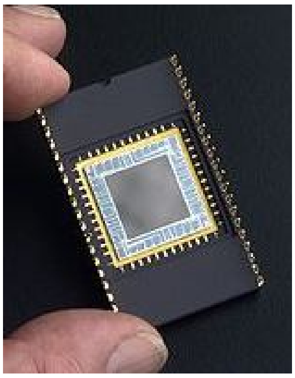
Light from a celestial object observed by a telescope. This light beam can be split into its component wavelengths by a spectroscope attached to the eyepiece of the telescope to examine astronomical spectra of celestial bodies.

A spectroscope is a device

Firstly, the light passes through several slits and then a collimator which uses measure astronomical spectra

A spectroscope is a device that spreads a light beam into its spectrum.

Charged coupled devices (CCDs) can detect very faint light signals. The new cryogenic superconducting S-cam that is still in development can record the position and colour of individual photons of light received. Observations can be made without intervening filters and prisms that would usually decrease sensitivity, functioning as an extremely sensitive spectrophotometer.



Charged Coupled device

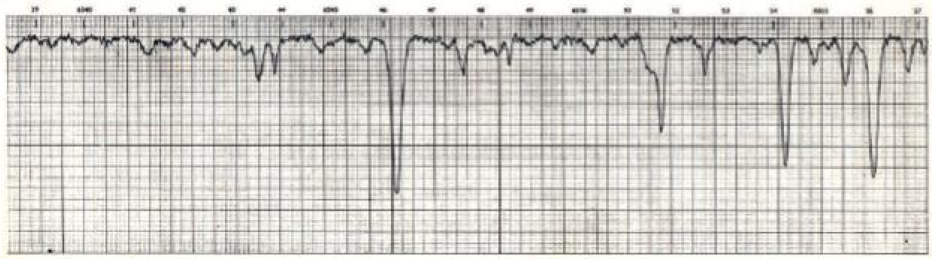
split into its component wavelengths by a spectroscope attached to the eyepiece of the telescope to examine astronomical spectra of celestial bodies.

Firstly, the light passes through several slits and then a collimator which uses mirrors or lenses to form the light into a flat vertical beam where photons move parallel to one another.

A dispersive element (either triangular prism or diffraction grating) splits the beam into its component wavelengths, dispersing it into a rectangular strip. A triangular prism separates light components by refraction, while a diffraction grating has thousands of narrow lines on a glass surface which causes the light passing through to diffract and interfere to produce an interference pattern, effectively dispersing the different wavelengths in a light beam. *While a prism cannot refract UV light, diffraction grating can also disperse UV component of light.*

The spread out spectrum can be recorded on a photographic plate where spectral emission lines appear as coloured lines on a dark background.

Alternately, spectra can be observed electronically using a photometer attached to the telescope. The intensity of each wavelength can be detected, producing a spectrum in the form of a graph. This setup is known as a spectrophotometer. Photomultipliers and CCD arrays can also be used.



Although spectroscopy was first based on the visible spectrum as they are more apparent. However, today, spectroscopy is no longer limited to electromagnetic radiation with appropriate electromagnetic sensors.

perform a first-hand investigation to examine a variety of spectra produced by discharge tubes, reflected sunlight, or incandescent filaments

Aim: To observe each of the three types of spectra - continuous, emission and absorption.

Equipment: Spectroscope, Gas discharge tubes, incandescent lamp, coloured solutions.

Method

(a) Turn on the incandescent lamp and examine its spectrum with spectroscope then describe it. Also examine reflected sunlight and compare the two.

(b) Turn on the gas discharge tubes (i.e. sodium), giving each time to warm up. Examine each with spectroscope, then describe its appearance.

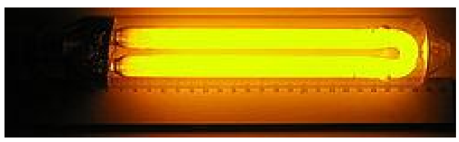
(c) Finally, turn on the incandescent globe and place a large beaker of coloured solution in front of it (i.e. $CuSO_4$, $KMnO_4$). View the light through the beaker using the spectroscope, compare the spectra seen through several different colourings.

Note that in each case, the spectrum is drawn with coloured pencils.

Spectroscope

Risk Assessment

Do NOT look directly at the sun through the spectroscopes given. High voltage discharge tubes should be set up by teachers and not handled by students.



Sodium Discharge Tube

Results

Spectra of an incandescent lamp is a continuous one, this is similar to reflected sunlight which appears to be continuous [although actually, sunlight is an absorption spectra as some discreet wavelengths are absorbed by cooler gas in the outer atmosphere of the star (i.e. hydrogen).]

Spectra of gas discharge tubes is an emission spectra which is different for every element viewed. Gases are at low density and after electrons in the atoms are excited by electric discharge, they soon drop back to a lower energy level emitting a photon of the precise difference in energy between the two shells with frequency given by E=hf. Since many such transitions are possible and each element has different electron transitions, the emission spectrum given by each element is different.

Spectra of coloured solution in front of a globe gives an absorption spectra, as the complement of the colour being transmitted is being absorbed.

Incandescent filament from a light bulb

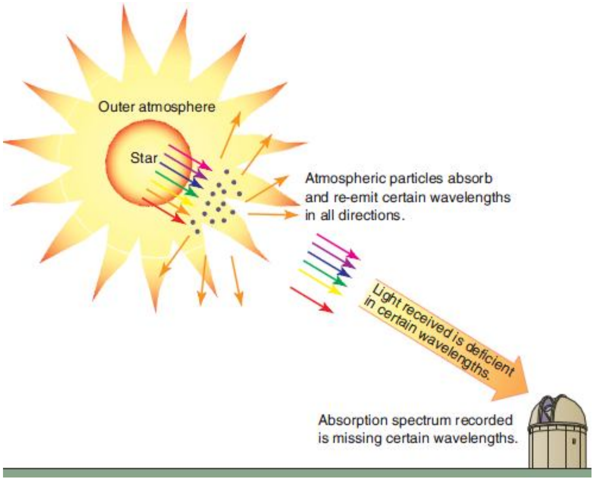
- identify the general types of spectra produced by stars, emission nebulae, galaxies and quasars

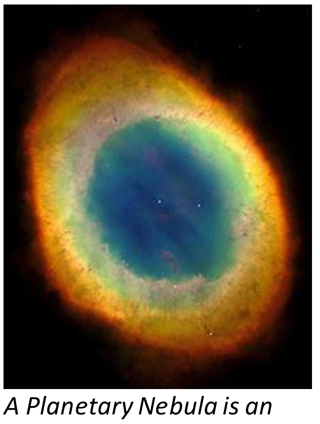
Body	Stars	Emission Nebulae	Galaxies	Quasars
Spectra type	Absorption spectra	Emission spectra	Continuous spectra	Continuous spectra (some emission)

Stars

Stars produce an absorption spectra. Although the inner layers of a star approximates the output of a black body, which produces a continuous emission spectrum, the cooler and less dense atmosphere absorbs certain wavelengths and re-emits them in all directions. This reduces the intensity of those absorbed wavelengths, producing an absorption spectrum with dark lines corresponding to discreet wavelengths being absorbed, in front of a continuous spectra background.

Gas atoms can only absorb photons of energy corresponding to the difference in energy levels: $E_2 - E_1 = hf$, and each element has their own unique set of electron transitions. Hence, by analysing the absorbed wavelengths in the absorption spectra of stars, the elements and molecules present in the star's atmosphere can be determined (i.e. hydrogen in F class and TiO in M class stars).





A Planetary Nebula is an example of an emission nebula

Emission Nebulae

These are vast regions of gas and dust, producing an emission spectra as they are illuminated with UV radiation from nearby stars.

UV radiation from hot, young stars within or behind the nebulae continually ionises the gases. When these ions recombine with free electrons to form excited atoms, excited electrons drop to a lower energy level as they emit photons with energy corresponding to the difference in energy level: $E_2 - E_1 = hf$.

The photons released produces an emission spectra which is **characterised mainly by hydrogen emission spectral lines**.

Galaxies

Galaxies are made of billions of stars and produce a continuous spectra that is a composite of various component spectra. Commonly, galaxies are dominated by old populations of stars that produce a red continuous spectrum dominated by calcium absorption spectral lines. New galaxies with numerous star formations are typified by intense emission spectra dominated by hydrogen emission spectral lines due to emission nebulae.

However, nearly all galaxies are moving away from us, and spectral lines of galaxies are red-shifted. The further away the galaxy, the faster its receding from us and the greater the degree of red-shifting.

Quasars

Quasars are believed to be super massive black holes at centre of young galaxies that emit light, radio waves and x-rays as they consume matter. They emit 10-1000 times as much radiation as a whole galaxy and are often significantly red-shifted. A quasar emits a continuous spectra at all wavelengths while a few emission lines fluctuate in intensity rapidly.

- describe the key features of stellar spectra and describe how these are used to classify stars

AND

- describe how spectra can provide information on surface temperature, rotational and translational velocity, density and chemical composition of stars

The stellar spectrum is the spectrum of radiation emitted by a star. Stellar spectroscopy applies the technique of spectroscopy to analyse starlight. This allows us to:

- Classify stars
- Obtain a great deal of information to learn more about their surface temperature, rotational and translational velocity, density and chemical composition (spectral 'fingerprint')
  - Even chemical composition of stars, nebulae and galaxies are found through stellar spectra.

Spectral Classification

Although most stars have similar chemical composition (similar sets of elements and compounds), their spectra can vary considerably. This is because at different temperatures, different atoms and molecules produce spectral lines of different strength.

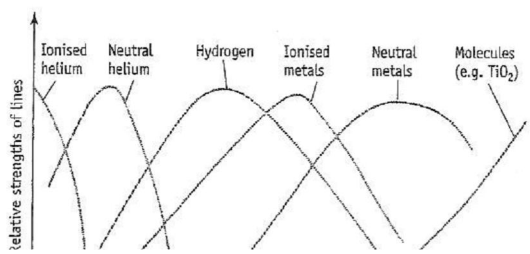
Stars have been classified according to a set of spectral classes designated by a letter according to the main spectral lines evident. In order of decreasing surface temperature, spectral classes are O, B, A, F, G, K, M.

Each spectral class is further divided into subgroups by attaching a digit (0 to 9) following the letter. With 0 being the highest temperature of that class, and 9 being the lowest.

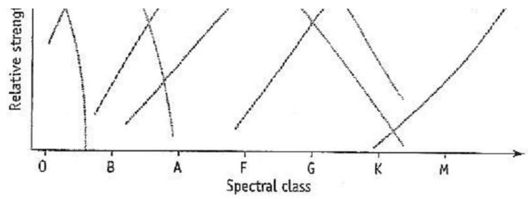
I.e. …-B8-B9-A0-A1-A2-…-A8-A9-F0-F1-…

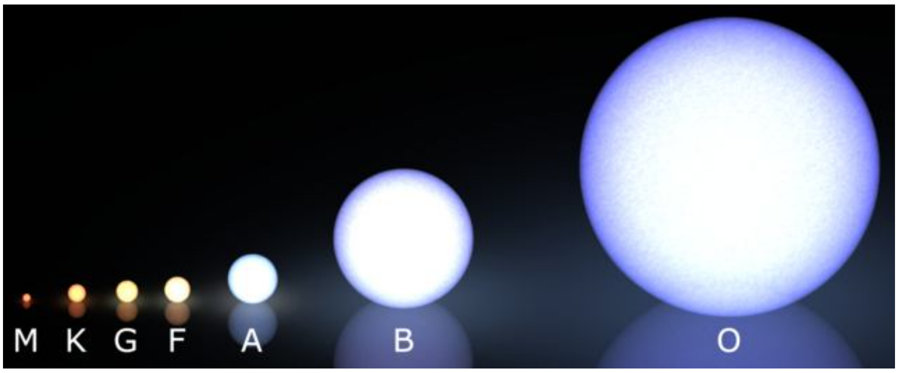
Spectral Class	Surface temperature (K)	Colour	Mass (Sun=1)	Spectral Features	Examples
O	>28000	Blue	30	Relatively few absorption lines; hydrogen lines very weak; **lines of ionised helium** and other highly ionised atoms. **Strong UV component**	Zeta Puppis
B	28000-10000	Blue-White	8	Stronger hydrogen lines; **lines of neutral helium**	Rigel, Spica
A	10000-7500	White	2.5	**Strong hydrogen lines; lines of ionised metals**	Sirius, Vega
F	7500-6000	Yellow-White	1.4	Weak hydrogen lines; **strong lines of ionised heavier metals; lines of neutral metals**	Canopus, Procyon
G	6000-5000	Yellow	1.2	**Lines of ionised metals (predominantly calcium); lines of many neutral metals present**	Sun, Capella
K	5000-3500	Orange	0.7	**Lines of neutral metals dominate**; hydrogen lines quite weak	Aldebaran, Arcturus
M	3500-2500	Red	0.3	**Strong lines of neutral metals**; **strong lines of molecules** (particularly TiO)	Betelgeuse Antares

The trend is such that lower temperature stars (i.e. M class) with temperatures 2500-3500K produce spectral lines characteristic of molecules (i.e. TiO) and hydrogen lines are usually absent. However, as temperature increases, more metal spectral lines and then ionised metal spectral lines become more evident while molecular lines decrease. Hydrogen lines increase until temperature is high enough to show helium then finally ionised



then ionised metal spectral lines become more evident while molecular lines decrease. Hydrogen lines increase until temperature is high enough to show helium then finally ionised helium lines evident in O class stars with surface temperatures of >28000K. Strength of hydrogen absorption lines are a good indicator of a star's surface temperature.





About 1 in 3,000,000 stars are class O stars and contain some of the most massive stars. This class is the rarest and has the highest temperature, appearing blue-white, emitting most of its output as UV.

Although class M seems to be composed of stars small in size, in actual fact, many giants and supergiants (i.e. Antares, Betelgeuse) also lie in this category, in addition to many smaller stars. 76% of main sequence stars are Class M stars.

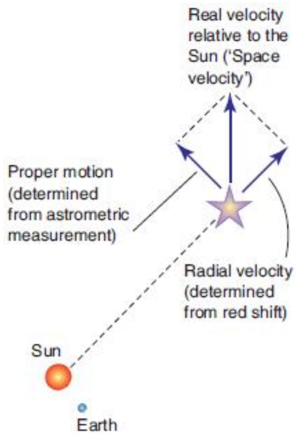
Inferred information

Surface Temperature

Surface temperature can be deduced once a star's spectral class has been identified from its main spectral lines. Alternately, a spectrophotometer can be used to determine intensity of wavelengths to discover wavelength of maximum energy output. Then a star's surface temperature can be calculated using Wien's Law (obtaining surface temperature in this way would also suggest spectral class and hence composition of the star).

Relative translational velocity

If a star is moving away from us, its spectral lines are red-shifted as they are a few nanometres closer to the red end of the spectrum; while if spectral lines are blue shifted if it's moving away. This is due to the Doppler effect, and by measuring the extent of wavelength shift, the radial velocity of a star (velocity towards or away from us) can be calculated. If this is combined with the proper motion of the star by astrometric measurements (sideways velocity seen by us), then a star's real velocity relative to the sun can be deduced.



Rotational velocity

Smaller Doppler shifting can be caused by a star's own rotational velocity, or participation in a rotating double star system.

In the case of a single, rapidly rotating star, light from the side of the star approaching the observer will have its spectra slightly blue-shifted, while light from the side receding has its spectra slightly red-shifted. Hence, a star's rotation produces a slight but simultaneous blue and red shift which broadens the spectral lines. The faster the star rotates, the greater this Doppler broadening effect is.

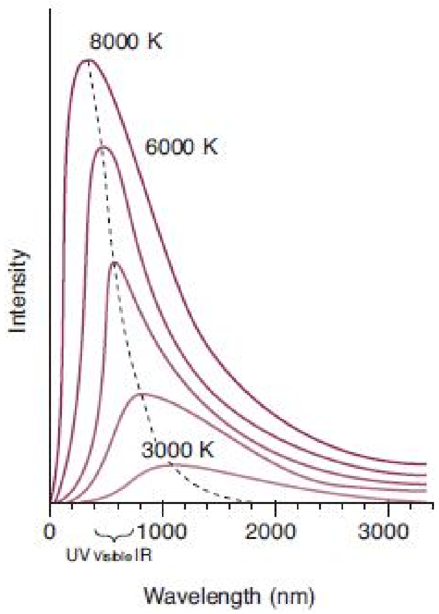
For a binary system seen on its edge by us, alternating blue and red shifting occurs as when one star moves towards us and its spectra is being blue-shifted, while the other is moving away and is being red-shifted. This alternating blue and red shifting results in the characteristic periodic doubling of lines typical of spectroscopic binary systems. Keeping track of this determines rotational period and velocities.

Density

Spectral lines of a star are also broadened by high density and pressure within its atmosphere. This effect is progressive as the greater the atmospheric density and pressure, the greater the pressure broadening of spectral lines. A supergiant star with particularly low density atmosphere has much narrower spectral lines than that of a more dense main sequence star (i.e. our Sun) of the same spectral class.

Chemical composition
The absorption spectrum from a star can be compared with known absorption and emission spectra for elements, ions and molecules on Earth. The high surface temperatures of the star vaporises elements and stellar spectra are characterised by typically absorption spectra of gases.

analyse information to predict the surface temperature of a star from its intensity/wavelength graph



A star's output is very similar to that of the radiation emitted by a black body. At a particular temperature, the radiation emitted is distributed continuously, but not evenly with the curve peaking at a certain intensity corresponding to a particular frequency for that particular temperature.

As temperature increases, the peak move towards the shorter wavelengths. Although at infra-red, the radiation lies mostly in the infra-red region, increased temperature moves the peak into visible spectrum and even into ultraviolet.

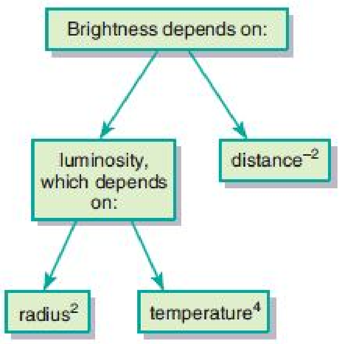
This relationship is described by Wien's law:

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

λ_{max} = wavelength of maximum output (m)
T = Temperature (K)
W = constant = 2.9×10^{-3} mK

As a star's output closely approximates that of a black body, its temperature can be determined from its intensity-wavelength graph. The wavelength of maximum output can be measured using a spectrophotometer, and the surface temperature can be calculated using Wien's law.

4. Photometric measurements can be used for determining distance and comparing objects.



The measurement of the brightness or flux of electromagnetic radiation from stars or other celestial objects is known as photometry.

Recap

The luminosity of a star is the total energy radiated by it per second, measured in watts. It is essentially the rate of energy output of a star, (aka intrinsic or absolute brightness), dependent on the star's temperature and radius.

The brightness of a star is a measure of the intensity of radiation reaching the Earth from the star, depending on the luminosity from the star, as well as its distance from Earth.

Therefore, stars vary in brightness, and due to the difference in distance between the Earth and the star, differences in brightness must be considered.

- define absolute and apparent magnitude

If a star's distance is less than 10 parsecs away, then its absolute magnitude would be more positive than the apparent magnitude. And the converse is also true.

If a star was more luminous than the other, but they have the same spectral class (and hence surface temperature), then the star must have a bigger radius due to Stephan-Boltzmann's Law where L is proportional to not just T^4, but r^2. Therefore, the two stars differ by radius and hence a bigger surface area which means greater luminosity.

Note that Stephan's law takes into account surface temperature and total luminosity to calculate surface area of a star. This surface area can then be used to calculate the radius, assuming the star is spherical.

Magnitude for stars is a brightness or intensity scale where a difference of 5 units between stars means a star is 100 times brighter than the other.

Absolute magnitude is the magnitude that a star would have when viewed from a standard distance of 10 parsecs. It is denoted by the symbol *M* and allows comparison of the luminosity (or intrinsic brightness) of the star without regard to distance.

Whereas, apparent magnitude is the magnitude given to a star as viewed from Earth; denoted by *m*. This is a measure of the brightness of a star, influenced by the distance of the star from Earth, its intrinsic brightness and intervening matter (i.e. interstellar dust).

The difference is clear, for example, Achernar and Betelgeuse have absolute magnitudes of -2.8 and -5.14 respectively. However, both stars look the same brightness as Betelgeuse is much further away than Achernar.

Magnitude scale

The first established scale for the magnitude of stars defined the brightest star seen in the sky as magnitude 1, while the faintest star as magnitude 6. In effect, this scale measured the apparent magnitude of stars, and was a reverse scale as the lower number indicated brighter stars.

Since then, the scale has been extended as dimmer stars are seen using telescopes

Hipparchus first pondered the concept of measuring and comparing the brightness of stars, and came up with the scale.

- explain how the concept of magnitude can be used to determine the distance to a celestial object

How can the concept of magnitude be used to determine the distance?

Define absolute magnitude

Describe the ways absolute magnitude can be determined

- If the orbital plane of a binary system is known, then an individual star's distance from the system's centre of mass is known. Hence, mass of individual stars can be determined. The mass-luminosity relationship can be used to find the luminosity and hence the absolute magnitude of the star.
- Broadening of spectral lines can be used to determine the mass of the star, and the mass-luminosity relationship can be used, to determine luminosity and hence absolute magnitude
- Determining the periods of Cepheids can be used to determine the absolute magnitude as they are directly proportional
- When a supernova occurs, and the type is known, then the energy output is known and the

absolute magnitude determined.

Define apparent magnitude

Describe way of measuring apparent magnitude (using ground based or satellite photometry)

Briefly describe the formula. (Absolute and apparent magnitudes use the same scale. If absolute magnitude and its distance is known (10pc), then if apparent magnitude is known, its distance can be found using <quote formula>)

solve problems and analyse information using:

$$M = m - 5\log\left(\frac{d}{10}\right)$$

and

$$\frac{I_A}{I_B} = 100^{(m_B - m_A)/5}$$

to calculate the absolute or apparent magnitude of stars using data and a reference star

Brightness Ratio

Pogson proposed that the human eye doesn't respond to light increases linearly but logarithmically as a light of magnitude 1 was approximately 100 times brighter than one with magnitude 6. This is expressed mathematically as:

$$\text{If } m_B - m_A = 5 \text{ then } \frac{I_A}{I_B} = 100$$

Therefore,

$$\frac{I_A}{I_B} = 100^{\frac{(m_B - m_A)}{5}}$$

Where m_A = magnitude of star A (brighter star)

m_B = magnitude of star B (dimmer star)

I_A/I_B = brightness ratio of the two stars.

For example, two stars one of magnitude 5 and the other 6, $m_A = 5$, $m_B = 6$. The brightness ratio would be $100^{(1/5)} = 2.512$. The difference in one magnitude was therefore, $10^{1/5} = 2.512$ times the brightness.

This ratio occurs with any two magnitudes with a difference of one, and is known as the Pogson's ratio. The Pogson scale also includes magnitude differences of greater than one, which translates into a brightness ratio for each case.

MAGNITUDE DIFFERENCE BETWEEN TWO STARS	BRIGHTNESS RATIO OF THE STARS
0	$2.512^0 = 1$
1	$2.512^1 = 2.512$
2	$2.512^2 = 6.310$
3	$2.512^3 = 15.85$
4	$2.512^4 = 39.81$
5	$2.512^5 = 100$
6	$2.512^6 = 251$
7	$2.512^7 = 631$
8	$2.512^8 = 1585$
9	$2.512^9 = 3981$
10	$2.512^{10} = 10\,000$

Questions relating to the brightness ratio simply compares the brightness of stars.

Don't mix up which one is the brighter star, note that the one that is more negative is brighter, hence it is m_A.

Remember significant figures! It answer is 17378 and it's correct to 3sf, must round to 17400.

For a star, given apparent magnitude at a distance, and asked to find the apparent magnitude at another distance.
Note that there are two magnitudes, so brightness ratio formula can be used.
Now distance will need to be converted to the brightness ratio. This can be done using the inverse square law: $I \propto 1/d^2$, so that $I_1 \propto 1/d_1^2$ and $I_2 \propto 1/d_2^2$.
Now $I_1/I_2 = d_2^2/d_1^2$, and hence the distance becomes the brightness ratio, and the value for apparent magnitude of one can be solved.

The sun has a magnitude of -26.8, while Sirius has a magnitude of -1.4. How much brighter does the Sun appear compared to Sirius?

$$\frac{I_A}{I_B} = 100^{\frac{(m_B - m_A)}{5}}$$

$$\frac{I_{Sun}}{I_{Sirius}} = 100^{\frac{(m_{Sirius} - m_{Sun})}{5}} = 100^{\frac{(-1.4 - -26.8)}{5}} = 100^{5.08} = 1.4 \times 10^{10}$$

Proxima Centauri is the closest star to our solar system, with a magnitude of 11. Calculate the brightness ratio of Algol (magnitude 2.1) compared to Proxima Centauri.

$$\frac{I_A}{I_B} = 100^{\frac{(m_B - m_A)}{5}}$$

$$\frac{I_{Algol}}{I_{Proxima}} = 100^{\frac{(m_{Proxima} - m_{Algol})}{5}} = 100^{\frac{(11 - 2.1)}{5}} = 100^{1.78} = 3600$$

Therefore, Algol appears 3600 times brighter than Proxima Centauri.

Distance Modulus

The close relationship between apparent magnitude and absolute magnitude and distance is expressed as:

$$M = m - 5\log\left(\frac{d}{10}\right)$$

Where M is absolute magnitude, m is apparent magnitude, d is distance (pc).

Other useful expressions include the distance modulus (*m*-*M*)

$$m - M = 5\log\left(\frac{d}{10}\right)$$

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

If given multiple filters, the apparent and absolute magnitude through the red filter is used.

For example: Achernar has an apparent magnitude 0.45 and an absolute magnitude of -2.77, calculate its distance. *[Note, M=-2.77, m=0.45]*

$$M = m - 5\log\left(\frac{d}{10}\right)$$

$$-2.77 = 0.45 - 5\log\left(\frac{d}{10}\right)$$

$$-3.22 = -5\log\left(\frac{d}{10}\right)$$

$$0.644 = \log\left(\frac{d}{10}\right)$$

$$\therefore \frac{d}{10} = 10^{0.644} = 4.4$$

$$\therefore d = 4.4 \times 10 = 44 \text{ pc}$$

The next example uses annual parallax and the distance modulus:
Altair has a parallax of 194.44 milliarcsec and an apparent magnitude of 0.76.
Calculate:
(a) Its distance
(b) Its absolute magnitude

(a) $d = \frac{1}{p} = \frac{1}{0.194\,44}$
$= 5.14 \text{ pc}$

(b) $M = m - 5\log\left(\frac{d}{10}\right)$
$= 0.76 - 5\log\frac{5.14}{10}$
$= 0.76 - 5\log 0.514$
$= 0.76 - 5(-0.289)$
$= 2.2$

*Luminosity Classes

Considering black body radiation and temperature, it's clear that stars with similar temperatures can have very different luminosities (energy output). Accounting for this is eight luminosity classes indicated by Roman numerals after the spectra class. This acted as an extension of the spectral classification system.

Class	*Ia*	*Ib*	*II*	*III*	*IV*	*V*	*VI*	*VII*
Group	*Bright supergiant*	*Supergiant*	*Bright Giant*	*Giant*	*Subgiant*	*Main sequence*	*Subdwarf*	*White dwarfs*

This is an important consideration for spectroscopic parallax detailed later.

■ outline spectroscopic parallax

An H-R diagram is a graph of absolute magnitude (or luminosity), versus temperature or spectral class. When many stars are plotted on an H-R diagram, certain star groupings become apparent.
These include: main sequence, red giants, white dwarfs.

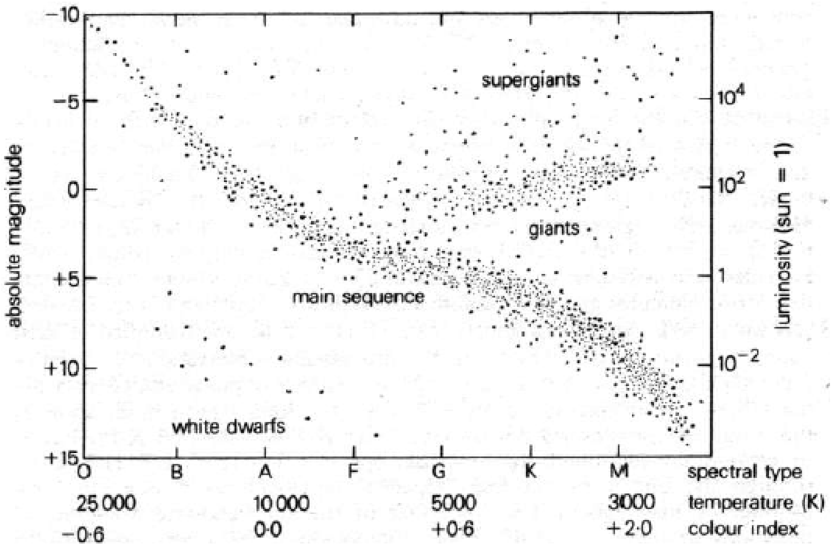
This is a method of using the H-R diagram and distance modulus formula to determine the approximate distance of a star.

The method involves:

1. Using photometry, measure the apparent magnitude, *m*, of the star being studied.
2. Using spectroscopy, determine the star's spectral class.
3. Also note the width of spectral lines to determine the luminosity class to find which group the star belongs to.
4. The H-R diagram is consulted. Locate the appropriate spectral class on the horizontal axis and draw a vertical line to the middle of the correct star group. From this approximate position, the horizontal line can be drawn across to the vertical axis to read off absolute magnitude, *M*.
5. With both *m* and *M*, the distance modulus formula can be applied to find the distance, *d*.

Although this technique can be applied to many stars, it can only be used for approximation as the value obtained for absolute magnitude has a large percentage error, and hence the calculated distance will have a large error.

As it is only an approximation, it is only used to give a 'ball-park' figure when no other techniques can be used.



E.g.1, Distance to Aldebaran
Aldebaran has apparent magnitude of 0.9, belonging to K5 spectral class and luminosity class III which means it's a red giant.
[Sol] Using the H-R diagram, locating the middle of the giants group from K5 spectral class, the read absolute magnitude of approximately 0. Therefore, distance modulus can be applied.
... d = 15pc. However, in reality, annual parallax of Aldebaran is 50 milliarcsec which gives distance of 20pc.

E.g. 2, Distance to Proxima Centauri
Proxima Centauri is an M5V star with apparent magnitude of 11. Determine its distance using spectroscopic parallax.
[Sol] Luminosity class V indicates it's a main sequence star. Reading up from M5 to the centre of the main sequence group, we determine an absolute magnitude of approximately 12.5. Hence distance modulus can be applied... d=5pc.
Actually, Proxima Centauri is 1.3 pc away with an absolute magnitude of almost 15.5

explain how two-colour values (eg colour index, B-V) are obtained and why they are useful

The brightness of the star depends on the colour sensitivity of the measuring device and the method used.

Visual magnitude refers to the magnitude judged by eye, which is a sensitive discriminator as the eye is most sensitive to the yellow-green portion of the visible spectrum. However, magnitudes determined this way are not judged to be as bright as they really are.

Photographic magnitudes were measurements of star magnitudes determined photographically. However, these were inconsistent with visual magnitudes as photographic film is most sensitive to the blue end of the visible spectrum. Hence, blue stars were measured brighter than the eye, while yellow and red stars were measured fainter.

Today, photometers are sensitive devices used to measure magnitudes much more accurately. To maintain consistency, a yellow-green V (visual) filter can be used to simulate visual magnitude measurements, and a blue filter (B) simulates photographic magnitudes. Additionally, the ultraviolet filter (U) utilises the extra sensitivity of the photometer beyond the visible spectrum. Together, this is the UBV system.

A red star, i.e. Betelgeuse, appears brightest through the V filter, so its V magnitude will be lower than its B or U.

A blue star, i.e. Rigel, appears brightest through the B filter, so its B magnitude is lower than its V or U.

NAME	COLOUR	CENTRE WAVELENGTH	BASED UPON
U	Ultraviolet	365 nm	—
B	Blue	440 nm	Photographic magnitude
V	Yellow–green	550 nm	Visual magnitude

This standard set of coloured filters is used in front of a photometer to measures the three different colour magnitudes for a star.

The advantage of the colour magnitudes is that they are numbers and comparisons can be made numerically using colour index.

Colour Index

Subtracting one colour magnitude from another results in a numerical two-colour value. The most standard of this type is the colour index, which is the difference between the photographic magnitude, B, and the visual magnitude, V.

Colour index = B - V

Applying this formula results in a numerical scale that expresses colour.

Red Star	Blue Star
Brighter through a V filter than a B	Brighter through a B filter than a V
V magnitude is lower than its B magnitude	B magnitude is less than its V magnitude
Hence, B - V will be a small positive number	Hence, B-V results in a small negative number

By definition, A0 spectral class stars have a colour index of zero. A0 class stars have a surface temperature of 10000K and a blue white colour.

Through the range of the colour index scale, it correlates with colour, spectral class and temperature.

COLOUR INDEX	COLOUR	SPECTRAL CLASS	TEMPERATURE (K)
−0.6	Blue	O	28 000–50 000
	Blue	B	10 000–28 000
0	Blue–white	A	7500–10 000
	White	F	6000–7500
+0.6	Yellow	G	5000–6000
	Orange	K	3500–5000
+2.0	Red	M	2500–3500

Note that this relationship between colour index and surface temperature is not linear.

If a spectrophotometer is available, Wien's law can be used to give a more accurate value for the star's temperature.

Colour Index Range	Temperature range
-0.6 to 0.0	40000K
0.0 to +0.6	4000K

Three stars are measured to have colour indexes of +0.5, 0.0 and -0.5, what can be said of each star?
[Sol]The first star has colour white-yellow, with spectral class of about F5 and surface temperature of approximately 6500K.
The second star is blue-white, with spectral class A0 and surface temperature of approximately 10000K.
The third star is blue, spectral class of about O5, with temperature of around 30000K to 40000K.

- describe the advantages of photoelectric technologies over photographic methods for photometry

Photometry involves measuring of the brightness or magnitude of a source of light such as a star, which can be done in a photographic or photoelectric manner.

Photographic methods

Photographic photometry can be done by making a photograph of a portion of the sky using specially prepared **emulsions**. Brighter stars expose a larger area of the film, and appear on the photograph as a larger, denser dot compared to a dimmer star.

After the photograph is developed, the size and density of the spot made by each star is measured and then compared to standard spot sizes and densities to determine the stars' magnitudes.

However, photographic emulsions are limited to the visible spectrum including near-infra-red and near-ultraviolet. Furthermore, some emulsions restrict this range even further.

Although fine details and higher resolution can be achieved photographically than electronically.

Photoelectric methods

Today, photoelectric photometry is more common, as these systems use a combination of filters and a detector. The detector is an electronic sensor such as a photomultiplier tube, or a charge coupled device (CCD) which is a light-sensing array. Both devices convert light input into electrical signals to be amplified, digitised, analysed and stored electronically.

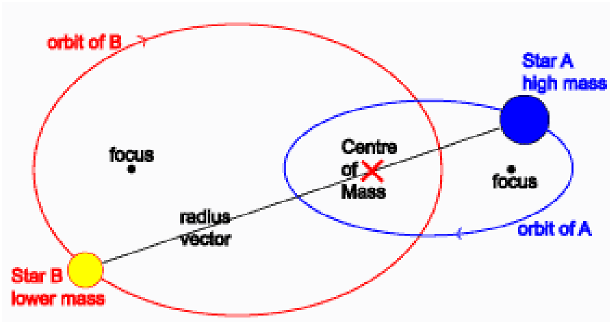
The system is flexible as this can be done quickly and remotely if necessary, producing easily digitised images. Furthermore, these devices are not only more sensitive to the visible spectrum and can detect fainter light sources than photographic emulsion, but are also sensitive to a wider range of wavelengths. Hence, with specific filters, they can detect intensities using the UBV system, or search for specific narrow bands that indicates a presence of a particular element in a celestial object. This lends photoelectric methods to greater range of applications and uses.

Despite these advantages, one disadvantage is that currently, photoelectric photometry cannot achieve the same resolution, however future technologies may improve this.

5. The study of binary and variable stars reveals vital information about stars.

More than half the main sequence stars are binary stars, which are double star systems. They consist of two stars mutually attracted by gravity, each in elliptical orbits around their common centre of mass with the more massive star following a smaller ellipse orbit <right>. These stars have invaluably contributed to advancement of astronomy:

- Analysing the motion of binaries allow us to observe a star's gravitational effect on another object, allowing us to determine the mass of a star.
- An unresolved binary can appear as a variable, and the study of variables allows us to reliably measure distance.



Orbital period and distance of separation varies enormously. Some systems are so close that they touch and exchange material, while others have orbital period of hundreds of years and separated by thousands of AU.

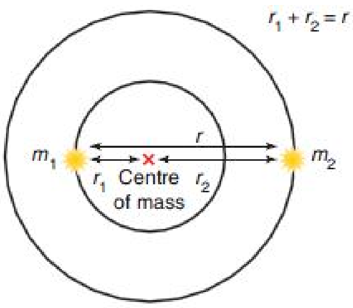
In a binary, stars are designated in descending order of brightness, with the brightest star carrying the letter A, the next with B (and so on if it is a multiple star system, i.e. Alpha Centauri C).

describe binary stars in terms of the means of their detection: visual, eclipsing, spectroscopic and astrometric

Classification of binary systems have been made according to the way they have been detected. They are placed into four groups: **visual, eclipsing, spectroscopic and astrometric.**

Visual Binaries

A visual binary is one where the component stars of the system can be individually resolved using a sufficiently powerful telescope. The motion of suspected visual binaries must be observed for many years as they might appear close only by line of sight (optical pairs). These systems tend to be close to us and physically widely separated, so that individual stars can be distinguished. Close long-term observation can determine the period of motion and the separation of the stars and the mass of the system can then be calculated.



A simplified binary system with circular orbits can be visualised such that the centre of mass of the system is at the point:

$m_1r_1 = m_2r_2$. But from diagram, $r_2 = r - r_1$, so that $\boldsymbol{m_1r_1 = m_2(r-r_1)}$

$$\therefore\ r_1 = \frac{m_2 r}{m_1 + m_2} \qquad r_1 = \frac{m_2 r}{M} \quad \text{where } M = m_1 + m_2.$$

Since the gravitational attraction between each star acts as the centripetal force of the star's orbit:

$$F_{\text{gravitational}} = F_{\text{centripetal}} \qquad \frac{Gm_1m_2}{r^2} = \frac{m_1v^2}{r_1}.$$

And substituting the relationship between orbital period and orbital speed:

$$v = \frac{2\pi r_1}{T}. \qquad \therefore\ \frac{Gm_2}{r^2} = \frac{4\pi^2 r_1}{T^2}.$$

By substituting the expression obtained for r_1, we get:

$$\frac{Gm_2}{r^2} = \frac{4\pi^2 m_2 r}{T^2 M} \qquad M = \frac{4\pi^2 r^3}{GT^2}$$

Note that rearranging this formula becomes Kepler's third law.

Where, M is the total mass of the binary system (kg)
m_1 and m_2 are the mass of star 1 and star 2 (kg)

r is the distance of separation (m)
T is the orbital period of the binary system (s)

This equation is used to calculate the mass of the binary system but not the mass of individual stars within the system. However, by measuring the distance of one of the stars to the centre of mass (r_1 or r_2), the individual masses m_1 and m_2 can be calculated. *Although this requires the inclination of orbit relative to us*. If this distance, is known:

$$m_1 r_1 = m_2 r_2 \qquad \frac{r_1}{r_2} = \frac{m_2}{m_1}.$$

And since we know the relations:

$$r_2 = r - r_1 \qquad M = m_1 + m_2$$

$$\therefore \frac{r_1}{r - r_1} = \frac{M - m_1}{m_1}, \qquad m_1 = \frac{M(r - r_1)}{r}$$

Where r_1 is the distance of star 1 from centre of mass of the binary system (m)

solve problems and analyse information by applying:

$$m_1 + m_2 = \frac{4\pi^2 r^3}{GT^2}$$

Calculating mass of binary system:

Sirius A and B have an observed period of 18295.4 days. If their separation is 3.0×10^9 km, calculate mass of the system.

[Sol]

18 295.4 days = 1.58×10^9 s

3.0×10^9 km = 3.0×10^{12} m

$$M = \frac{4\pi^2 r^3}{GT^2}$$

$$= \frac{4\pi^2(3.0 \times 10^{12})^3}{(6.672 \times 10^{-11})(1.58 \times 10^9)^2}$$

$$= 6.4 \times 10^{30} \text{ kg}$$

Also note a convenient form:

$$m_1 + m_2 = \frac{a^3}{T^2}$$

Where $m_1 + m_2$ is the total mass of the system (in solar masses $M_\odot$)
a is the distance of separation in AU
T is the period in years

Determining mass of stars within a binary system.

Stars in a visual binary are observed to have an orbital period of 1.8×10^8s and are 5.0×10^8km apart. The more massive star is 1.5×10^8km from the centre of mass of the system. Determine:

(a) The total mass of the system
(b) Masses of each star

(a) $$M = \frac{4\pi^2 r^3}{GT^2}$$

$$= \frac{4\pi^2(5.0 \times 10^{11})^3}{(6.672 \times 10^{-11})(1.8 \times 10^8)^2}$$

$$= 2.3 \times 10^{30} \text{ kg}$$

(b) $$m_1 = \frac{M(r - r_1)}{r}$$

$$= \frac{2.3 \times 10^{30}(5.0 \times 10^{11} - 1.5 \times 10^{11})}{5.0 \times 10^{11}}$$

$$= 1.6 \times 10^{30} \text{ kg}$$

$$m_2 = M - m_1$$

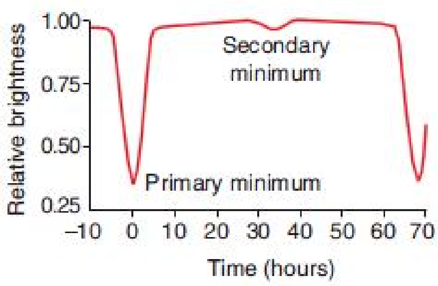
$$= 2.3 \times 10^{30} - 1.6 \times 10^{30}$$

$$= 0.7 \times 10^{30} \text{ kg}$$

Eclipsing Binaries

An eclipsing binary system is one viewed along the orbital plane of the star's orbits, *i.e. seen on edge by the observer*, such that through an orbit, the component stars periodically eclipses each other and blocks out each other's light. Photometric measurement of these binaries' apparent magnitude over time is performed by photoelectric means, a charge-coupled device or photometer connected to a telescope. Photographic images or visual observation is sufficient for brighter stars. The produced light curve (a graph of apparent magnitude versus time), shows the characteristic periodic primary eclipses (when hotter star passes behind cooler star), and a shallower secondary eclipse..

When the stars are side by side form our point of view, the binary system produces maximum light. During the primary eclipse, the brighter star is hidden by the fainter star and light



Note, if using apparent magnitude on vertical scale, m, lower no. is at the top, as it is brighter.

Many stars show a periodic change in apparent magnitude, and this can be due to:

- Change in intrinsic luminosity (i.e. pulsating variables) *binary system produces maximum light. During the primary eclipse, the brighter star is hidden by the fainter star and light received by us drops significantly. But during the secondary eclipse when the dimmer star is hidden, light received by us drops again, though not as much as during the primary eclipse.*

magnitude, and this can be due to:

- Change in intrinsic luminosity (i.e. pulsating variables)
- Eclipsing binary system

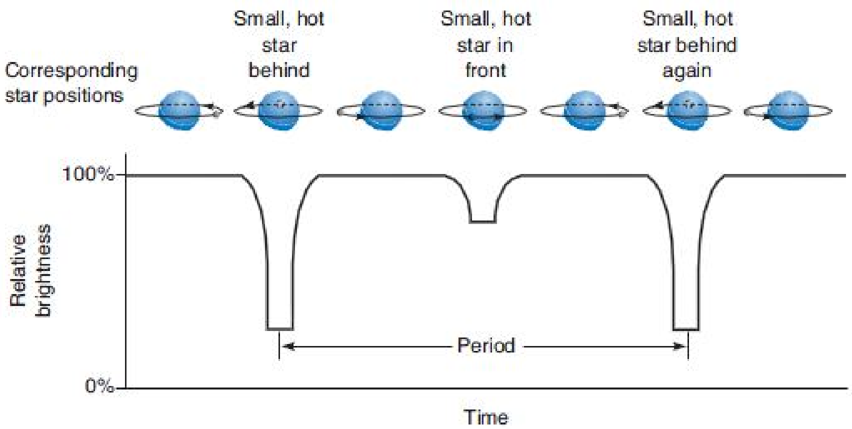
Photometry of characteristic light curve will confirm the identity of the star.

Hence we can determine:

- The period of motion by observing these variations in the light curve, showing a regular pattern of asymmetrical dips. The period is measured as the time between successive primary or secondary minima.
- Analysis of this light curve may allow astronomers to determine the eccentricity, orientation, and inclination of orbit.
- The radii of each star relative to their orbit size can also be determined by duration of eclipses.
- Ratio of effective temperatures of the two stars can also be calculated.

I.e. Algol A is a B8 main sequence star of 2.8 solar radii and 3.7 solar masses, while Algol B is a dimmer K2 sub-giant of 3.5 solar radii and 0.8 solar masses.

These two stars are of quite different sizes and when orbiting each other, the primary eclipse occurs with the larger dimmer star in front of the smaller brighter star. (Algol B in front of Algol A)



Generally, in a binary system, the primary eclipse is when the star designated B eclipses the star designated A, producing a primary minima in the light curve. While the converse is true for secondary eclipses producing a secondary minima.

This is because more flux is blocked in the primary minima when the cooler star blocks the hotter star. Note that the hotter the star, the more the luminosity ($L \propto T^4$)

Describe features of light curve suggesting an eclipsing binary: Regular decrease in intensity received by the star periodically - every T days. Apart from regular dips, intensity is uniform, unlike light curve of an intrinsic variable star (i.e. Cepheid). --> Explain this curve: While both stars are visible, light intensity remains at maximum, but total light received from the binary is reduced while one star eclipses the other.

If the light output drops by 1%, and $I \propto \pi r^2$, then a drop of 0.01 in intensity, corresponds to 0.01 of the area being covered up. Since $A=\pi r^2$, therefore, the dwarf covering 0.01 of the large star's area is 0.1 of its radius, i.e. $r^2=0.01$, therefore, $r=0.1$. But this is only a relative measure, and assuming the stars have perfect circle cross sections.

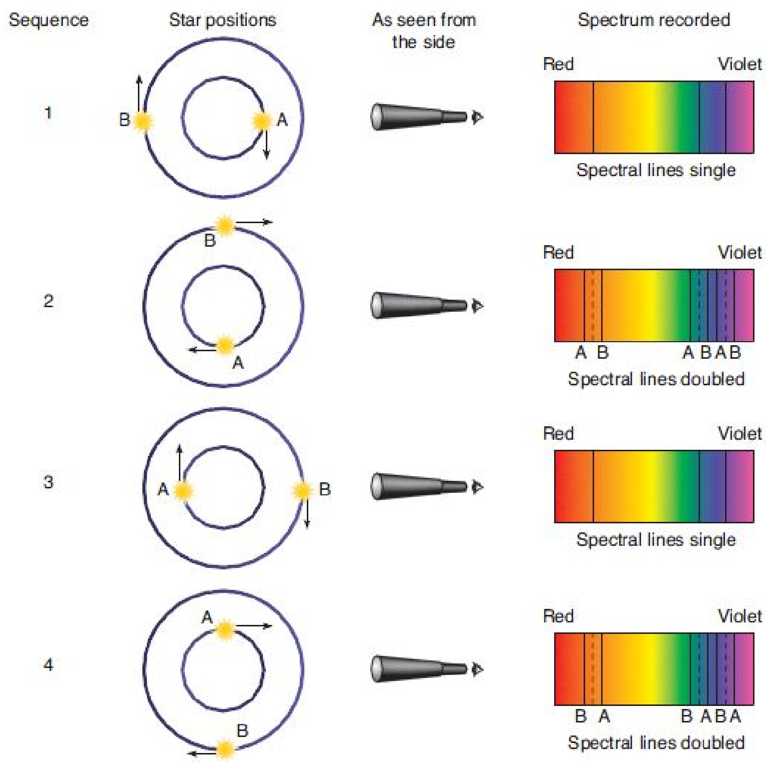
Spectroscopic Binaries

Most binary systems are too far away to be distinguished visually. A majority of unresolved pairs revealed to be binaries through alternating Doppler shifting of spectral lines are spectroscopic binaries. These systems are most likely detected when period is short, individual star velocities are high and the system is viewed along the plane of the orbits of the stars.

When stars move tangentially to an observer (i.e. across our line of sight), the spectral lines stay in their mean position and no Doppler shifting occurs. However, as stars move alternately towards and away from us, their absorption spectral lines are respectively blue and red shifted.

Sequence Star positions As seen from Spectrum recorded

This produces a characteristic



This produces a characteristic doubling of lines when red/blue shifting occurs to the individual star's spectral lines.

However, this analysis is limited: If component stars are low in mass, and/or far apart then the period will be long and velocity be low, reducing chance of detection. Further, Doppler shifts cannot be detected in systems with orbital planes perpendicular to our line of sight.

However, it is difficult to obtain the inclination of the plane of the orbit relative to us. Without this, individual masses of stars cannot be calculated.

When the plane

Systems that are both eclipsing and spectroscopic are useful as radial velocity from spectral data can be used to calculate absolute, rather than relative values for stellar radii. This is then combined with orbital inclination parameters obtained from the light curve to give stellar masses and densities.

Total luminosity of the system can be derived, and used to calculate total flux of system for distance calculations.

We can also establish a mass-luminosity relationship of each star.

Note, if spectral lines are broadened, then it shows that the star is rotating very fast around its own axis, or it is very dense.

Describe the spectroscopic observations that would determine whether a particular star is really a binary star system.
Define binary
Observe spectral lines using a spectroscope

- Spectroscopy can be used to determine unresolved binaries by observation of alternating Doppler shift of spectral lines resulting in the doubling of spectral lines characteristic of spectroscopic binary star systems.
- This is easily detected when the period is relatively short and the system is seen along its orbital plane.
- When stars move across the field of view, no Doppler shifting occurs. However, when one moves towards and one moves away, respective blue and red shifting occurs, and this occurs alternately as the motion is exchanged.

Astrometric Binaries

An astrometric binary has one star too faint to be observed. Through astrometric measurements and repeated observation, the visible star is seen to have a detectable perturbation or "wobble" in their proper motion. Therefore, the presence of an unseen (and hence dim) partner can be inferred.

The wobble can even reveal the period of orbit as well as its size; allowing the estimation of the mass of the system or possibly individual star masses.

Relatively few binaries have been detected in this way due to need for long term observation, and uncertainty in position and proper motion measurements. However, modern astrometric techniques have began discovering stars with even a very small wobble. This indicates a very small mass partner, evidence of planets with masses similar to Jupiter outside of our solar system. Though many are positioned quite close to their star.

Proper motion is the motion relative to the rest of the sky.

Notes

From these binaries, the period can be obtained:

- Visually by direct observation of the orbit over many years.
- Light curves (successive primary minima) for eclipsing binaries
- Via spectroscopy, when spectral lines return to the mean position twice.
- Long term astrometric measurements.

Observation over time allows the apparent relative orbit of systems to be plotted and the average distance of separation of component stars to be found. Hence the formula can be used: M=...

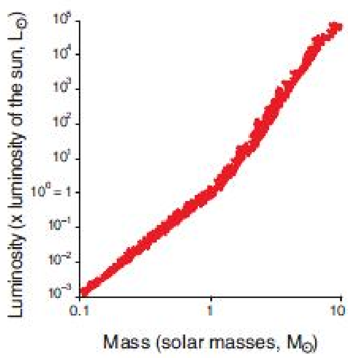
Describe how the existence of a binary star may be deduced (2marks)

Briefly define

Describe 2 methods

- Visible --> Resolve
- Spectrometry --> Doubling of spectral lines
- Astrometry --> Perturbation of visible star.
- Eclipsing --> Light curve, characterised by primary and secondary minima.

explain the importance of binary stars in determining stellar masses



Stellar masses can be determined using binary systems. A plot of luminosity against mass of main sequence stars reveals an apparent relationship. This mass-luminosity relationship reveals that for most main sequence stars, luminosity is proportional to the fourth power of its mass. I.e. $L \propto mass^4$.

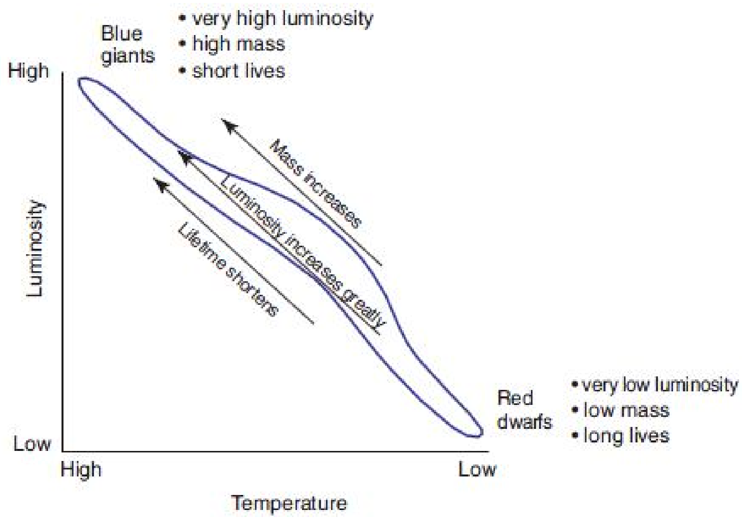
This is true of stars with a solar mass of between $.43M_\odot$ and $2M_\odot$. However stars smaller than $.43M_\odot$ follow a slightly different relationship.

$$\frac{L}{L_\odot} = \left(\frac{M}{M_\odot}\right)^4 \qquad (.43M_\odot < M < 2M_\odot)$$

$$\frac{L}{L_\odot} = .23\left(\frac{M}{M_\odot}\right)^{2.3} \qquad (M < .43M_\odot)$$

The mass-luminosity relationship has implications when interpreting the main sequence on the H-R diagram:

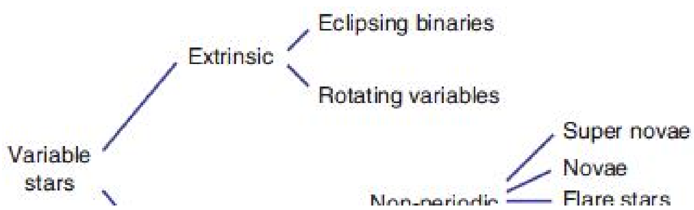
- As luminosity increases on the H-R diagrams, mass also increases, though not by much due to the fourth power relationship.
- The brighter and more massive stars have shorter lifetimes as they are more luminous and burn more fuel at a faster rate, despite having more fuel.



classify variable stars as either intrinsic or extrinsic and periodic or non-periodic

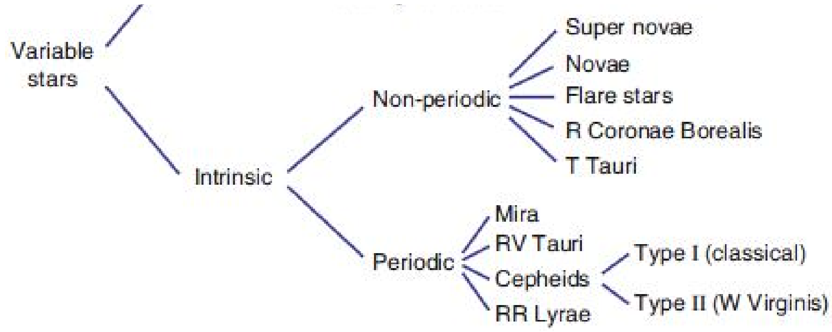
Stars which vary in apparent brightness over time as seen from the Earth is classified as a variable. There are different types of variable stars and more than 30000 have been recorded to date.

The stars are classified in a system which separates them as extrinsic or intrinsic variables. Intrinsic variable stars are further categorised into periodic (i.e. pulsating stars) or non



Intrinsic variable stars are further categorised into periodic (i.e. pulsating stars) or non-periodic (i.e. eruptive or cataclysmic stars).

Note variable stars are named from the brightest to the dimmest. They are designated letters R to Z, then RR to ZZ followed by the particular constellation they're in.



Extrinsic Variables

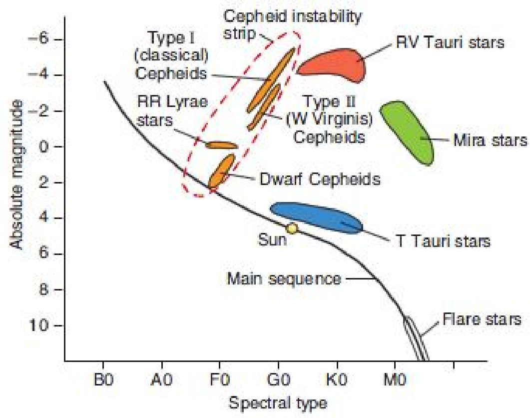
The variability of these stars are due to a process external to the star, i.e. eclipses or rotation:

- Eclipsing binaries vary in brightness as the stars eclipse each other during their orbits since their orbital plane is seen on its edge.
- Rotating variables have hotter or cooler areas on their surface which move in and out of view during the star's rotation, therefore, altering its brightness with time. I.e. Sizable sunspots.

Intrinsic Variables

In this case, brightness variation is due to changes in property within the star itself.

Intrinsic variable stars generally occupy specific locations on an H-R diagram and can be further classified into non-periodic and periodic variables.



Non-Periodic Variables

This group includes intrinsic variables which display irregular variations in brightness overtime:

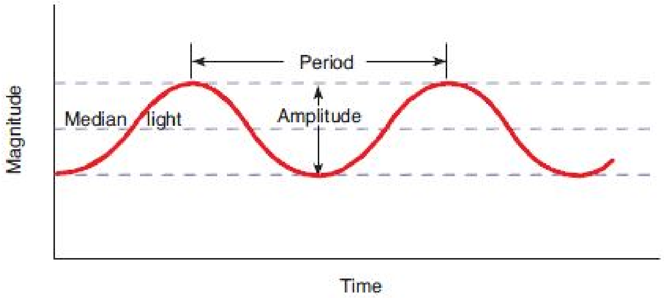
- A **supernovae** is a large star at the end of its life violently explodes due to gravitational collapse. Brightness temporarily increases by 20 magnitudes to an absolute magnitude of about -15 before fading away. The star is destroyed, leaving behind an expanding shell of gas and a high density, compact object (neutron star/black hole)
- A **novae** is a close binary star where hydrogen rich material is drawn from one star to the other, a white dwarf. Accumulation of sufficient material causes a reaction, creating a nova explosion resulting in the sudden increase in brightness of about 10 magnitudes. The star then returns to pre-nova magnitude, though a shell of gas may be ejected.
    - In an extreme case, too much mass accumulation from a companion star produces a runaway reaction sufficient to unbind the star leading to a 'type Ia' supernova, destroying the white dwarf.
- **Flare Stars** (i.e. UV Ceti stars) are red dwarfs which experience intense outbursts of energy from small areas of their surface. This results in a sudden increase in brightness of greater than 2 magnitude before returning to normal within an hour.
- **R Coronae Borealis** are supergiant stars. They are rich in carbon, which accumulates in the outer atmosphere and strongly absorbs the light. Hence, brightness suddenly decreases by about 4 magnitudes, before slowly fluctuating back to normal as the accumulated carbon is blown away.
- **T Tauri** are rapidly rotating young protostars still losing mass and contracting from the gas cloud in which they lie. Irregular unpredictable variations in the outer layers result in light. Although, this activity is obscured by gas clouds and must be observed using infra-red.

light. Although, this activity is obscured by gas clouds and must be observed using infra-red.

Periodic variables

These variables are observed to have a regular pattern of brightness variation, characterised by their light curve.

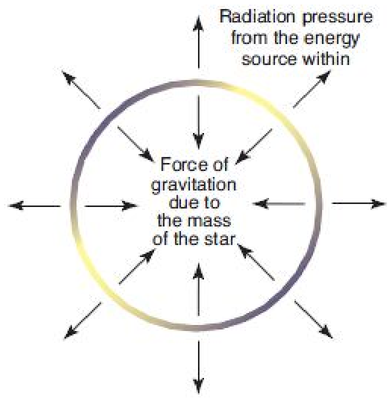
To the right is a generic light curve for periodic variables, showing parameters used for description.



In general, the regular fluctuation in brightness is due to a disequilibrium existing between the two forces that act upon a star to determine its size:

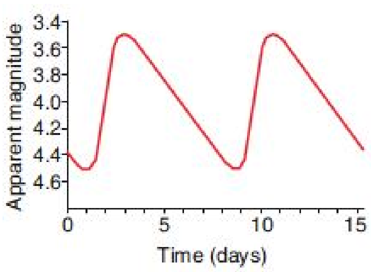
- The gravitational force and
- Its radiation pressure.

When the two forces are in disequilibrium, the star pulsates in size, temperature, luminosity and thus, brightness. Hence, these stars are also called pulsating variables.



Type	Period (days)	Amplitude (magnitudes)	Median light	Comments
Mira	80-1000	2.5-10	No typical value	Long period, pulsating red giants and supergiants
RV Tauri	20-150	No typical value	No typical value	Yellow supergiants, alternating deep and shallow minima on light curve
Cepheid	1-50	0.1-2	-1.5 to 5M	Very luminous yellow supergiants. Type I (young) and Type II (older).
RR Lyrae	<1	<2	0 to +1M	Old giants. Always have approximately a magnitude of +0.6

- explain the importance of the period-luminosity relationship for determining the distance of cepheids



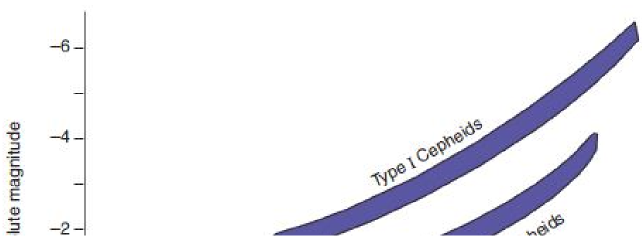
Cepheid and RR Lyrae variables are particularly important as they offer another means of distance measurement.

Cepheid variables located in the Small Magellanic Cloud are all at a similar distance from Earth. The typical light curve for Cepheid variables are distinct from other variables, consisting of a sharp increase in brightness followed by a slower decrease to complete the oscillation. In the early 1900s, it was recognised that Cepheids with longer periods of oscillation were also, on average, more luminous; now known as the period-luminosity relationship.

Two types of Cepheids exist consisting of:

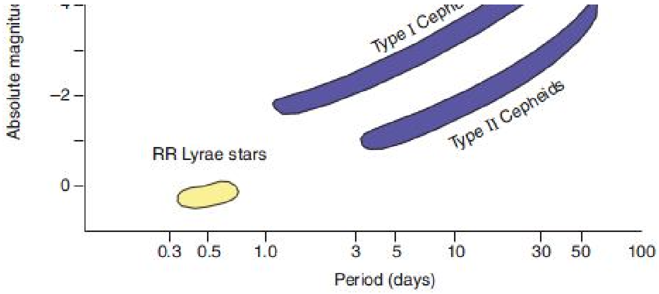
- Type I (or classical) Cepheids. Massive young, 2nd generation stars.
- Type II (or W Virginis stars). Small, old, red, 1st generation stars.

Their period luminosity relationship is shown below and allows their distance to be calculated.



To calculate the distance:

1. Using spectral analysis, establish the type of Cepheid being examined.
2. From the Cepheid's light curve, determine the period
3. From the period luminosity relationship, use the period to determine the star's average absolute



period
3. From the period luminosity relationship, use the period to determine the star's average absolute magnitude, *M*.
4. From direct observation, measure the star's average apparent magnitude, *m*.
5. Use the distance modulus formula *m*-*M*= 5log(d/10) to calculate the distance to the star.

Alternately, RR Lyrae variables can be used to calculate distance. Since they have a similar absolute magnitude of about +0.6, once a RR Lyrae variable is recognised and confirmed, a measurement of apparent brightness will allow distance calculation using the distance modulus formula.

Therefore, distance s within our galaxy and distances to neighbouring galaxies can be determined. Although, this method faces the limitation that interstellar dust can alter the apparent brightness, *m*, making it dimmer and results in the calculated distance being greater than the actual value.

Explain how observation of binary and variable stars can be used to infer physical property of these stars. (6 marks)
Define Binary
Describe each type

- For visual or astrometric binaries, the orbital period and the distance of separation can be determined by close measurement. Hence, the mass of the system can be determined by (m_1+m_2=…)
- Light curves of eclipsing binaries can be studied to determine their period; comparison of brightness can also be made. Furthermore, the duration of eclipse allows the comparison of relative size and measurement of diameter.
- Spectroscopic binaries can have their spectra observed as with any star, revealing density, velocity, temperature/colour and mass. Periodic variation in spectral lines allow spectral class to be estimated, and Doppler shifting of spectral lines determines rotational velocity.

Define Variable (stars without a constant light curve)
Describe Cepheids.

- Among these, are Cepheids whose light curves vary periodically. And the period of each Cepheid is proportional to its mean absolute magnitude, allowing this to be determined accurately. By comparing this with the mean apparent magnitude, their distance from Earth can be measured. Spectrum of a Cepheid indicates its colour spectral class/surface temperature changes periodically. Doppler effect of Cepheids show that they indeed expand and contract periodically.

perform an investigation to model the light curves of eclipsing binaries using computer simulation

The java applet at Cornell University simulated the light curve of the binary system. The distance of separation and spectral class of each star as well as the viewing angle of the system can be adjusted. A variety of settings are entered to observe the effect of these variables on the period and shape of the light curve.

As the angle of inclination increases, the primary and secondary minima become more defined, with the primary minima experiencing a greater reduction in brightness. However, if the angle of inclination is too great, and the orbital plane is close to vertical with the observer, then the two stars may no longer overlap with each other and the eclipsing does not happen.

Describe the modelling process used in a computer simulation which raws a light curve for an eclipsing binary star system.

- An eclipsing binary is identified by its characteristic light curve modelled by the computer program.
- Luminosity (magnitude) of the binary is graphed against time as a base and the modelling shows the light from the binary as observed from Earth.
- Modelling shows three phases
  - A – Normal maximum luminosity when both stars are visible
  - B – Primary minima (a dip) when brighter star eclipsed by dimmer companion
  - C – Secondary minima (a shallower dip) when dimmer star eclipsed by brighter companion
- Draw the light curve and represent position of stars at each critical point in the light curve. Label axis and everything. Add title to graph.

6. Stars evolve and eventually 'die'

- describe the processes involved in stellar formation

The Interstellar Medium

Stars are born out of the interstellar medium, which is the space between stars filled with sparse and irregular **gas** and grains of **dust**.

Interstellar gas mainly exists in large cold clouds, or nebulae, which covers broad regions. This **comprises mainly of hydrogen**, some helium and some other **trace elements** in the form of neutral atoms, **charged ions or molecules** (i.e. H_2O, NH_3, CO, etc.)

Ionised hydrogen in hotter, dense regions are easily observed as nebulae around hot stars since UV radiation given off by the stars are absorbed and re-emitted by the hydrogen ions at visible wavelengths.

Neutral hydrogen has been found more recently using radio telescopes, and are concentrated in the plane of the galaxy, giving off radiation with wavelengths of 21cm.

Molecular gas clouds are often several tens of light years across, with masses of a thousand solar masses and having densities of several billion molecules per cubic metre (most commonly hydrogen).

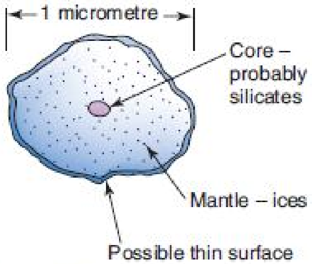


Figure 17.2 A model for the structure of an interstellar dust grain

Meanwhile, **interstellar dust** is more tenuous, having just one grain per cubic metre on average, possibly formed in outer atmosphere of a cool supergiant star before being blown away by the star's stellar wind. **Each grain of dust comprises of a core of silicates** (or iron or graphite), and a **mantle made of a mixture of ices** (H_2O, CO_2, CH_4, NH_3).

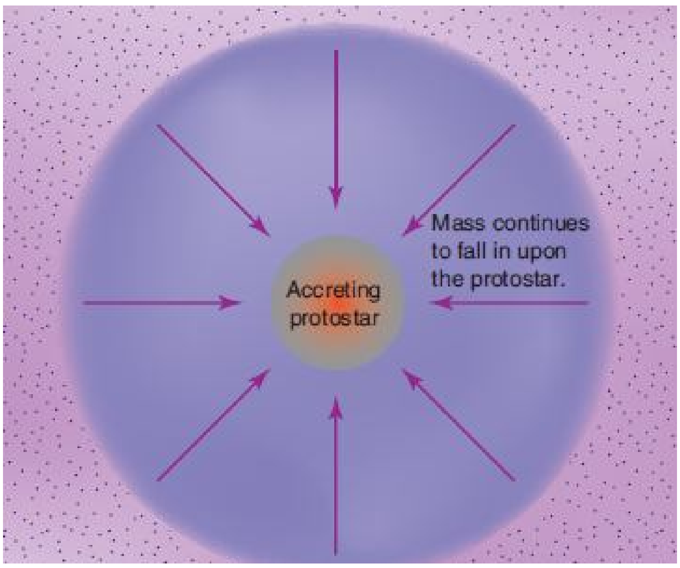
Dust clouds are detected as they can redden the light passing through as the bluer wavelengths get scattered and block out light by scattering and absorption. A dark nebula is an interstellar cloud with sufficient dust to completely block the light of stars or nebula behind it. (I.e. Horsehead nebula)

Dust grains act as sites of molecule formation in the interstellar medium. Hence, molecular clouds contain a lot of dust.

Although the dust obstructs our view optically, we can use infra-red and radio telescopes to reveal what's happening beneath the clouds.

Gravitational Collapse

A molecular cloud that's sufficiently cool and massive, contracts under its own gravity and this gravitational freefall speeds up as it draws itself in. The density increases most quickly at its centre, and being denser, the centre experiences greater gravity and contracts even faster. The separates the cloud into two parts, the rapidly contracting core, and the slower contracting surroundings.



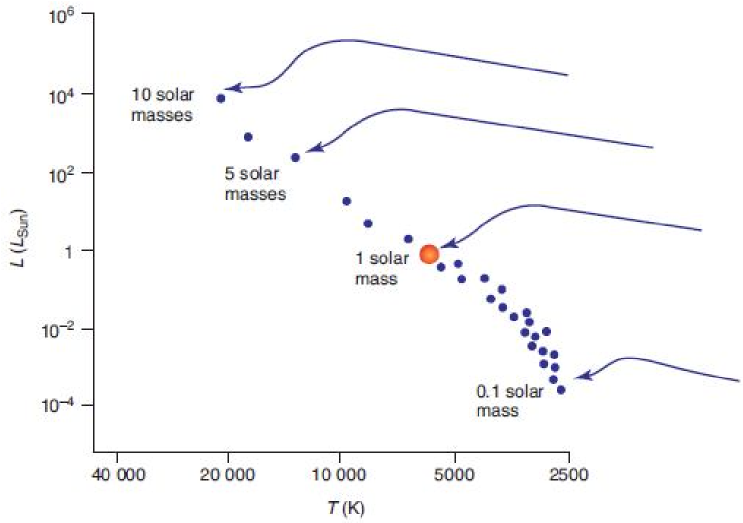
During contraction, gravitational potential energy of gas particles is converted into kinetic energy, so the core heats up. This heat creates an outward pressure working against gravitational collapse, slightly at first, but eventually slowing and stopping the collapse. This stabilises the size of the core, now called a protostar. This process takes approximately one million years, and the resulting protostar is hidden from our view due to surrounding molecular gas clouds containing obscuring dust.

Surrounding material still contracts and rains in on the protostar continually, causing it to increase its mass by accretion. It begins to behave as a T Tauri variable, developing strong stellar winds that sweep away the it to increase its mass by accretion. It begins to behave as a T Tauri variable, developing strong stellar winds that sweep away the remnants of the surrounding cloud. Subsequently, we can see the forming star with visible light.

Having no source of energy, the protostar begins a slow shrinkage, decreasing in size. Consequently, it becomes less luminous, but the temperature of the core increases further. With sufficient mass, the core may reach a temperature high enough to trigger nuclear fusion of hydrogen (8 million kelvin).

Fusion of hydrogen provides a long lasting energy source which stabilises the star. Now it is a zero-age main sequence (ZAMS) star, which is smaller but less luminous than the protostar. It's mass is between 0.1 and 100 solar masses. Any less and the protostar would not have heated sufficiently for nuclear fusion, any larger, and the protostar would have overheated and blown itself apart.

Generally, the gas cloud is several solar masses. During contraction, the conservation of angular momentum of the spinning cloud makes it spin faster, causing the cloud to fragment into smaller spinning parts. Hence, groups of stars are formed from the same gas cloud. Smaller spinning parts can further fragment leading to planet systems around stars.



The process of star birth can be traced on the H-R diagram. For a 1 solar mass star, the process takes approximately 50 million years. Stars with less mass take longer, while stars with more mass takes shorter.

A plot of zero-age main sequence (ZAMS) stars on the H-R diagram forms the complete diagonal, main sequence shape.

outline the key stages in a star's life in terms of the physical processes involved
AND
discuss the synthesis of elements in stars by fusion
AND
describe the types of nuclear reactions involved in Main-Sequence and post-Main Sequence stars
AND
explain the concept of star death in relation to:
- planetary nebula
- supernovae
- white dwarfs
- neutron stars/pulsars
- black holes

AND
analyse information from a H-R diagram and use available evidence to determine the characteristics of a star

The **stability of a star** throughout its life depends on the equilibrium it has achieved. There must firstly be **hydrostatic equilibrium**, the balance between outward radiation pressure and inward gravitational force. Secondly, there must be **thermal equilibrium**, which is the balance between the rate at which energy is produced in the core and the rate at which energy is radiated from the surface.

Main Sequence

After the protostar stage, a star of mass between 0.1 and 100 solar masses becomes a main sequence star, characterised by fusion of hydrogen to helium in its core, surrounded by unused or non-reacting, hydrogen layers.

Nuclear fusion provides a source of energy for the star in accordance with $E=mc^2$. There are two types of fusion reactions.

Proton-proton chain

The first to occur in main sequence stars is the proton-proton (p-p) chain. Nothing that v is neutrinos.

$$^1_1\text{H} + ^1_1\text{H} \rightarrow ^2_1\text{H} + e^+ + \nu$$

$$^1_1\text{H} + ^2_1\text{D} \rightarrow ^3_2\text{He}$$

Then when the above reactions take place twice,

$$^3_2\text{He} + ^3_2\text{He} \rightarrow ^4_2\text{He} + 2\,^1_1\text{H}$$

So overall:

AND

analyse information from a H-R diagram and use available evidence to determine the characteristics of a star and its evolutionary stage

Then when the above reactions take place twice,

$$^{3}_{2}He + ^{3}_{2}He \rightarrow ^{4}_{2}He + 2\,^{1}_{1}H$$

So overall:

$$4\,^{1}_{1}H \rightarrow ^{4}_{2}He + 2e^{+} + 2\nu$$

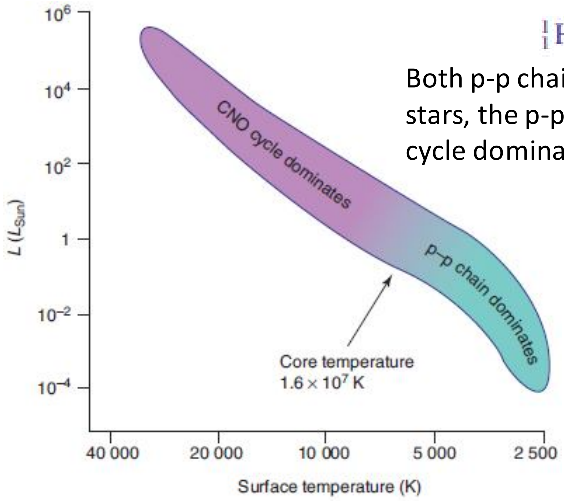
The helium produced by hydrogen burning collects at the centre of the star as it's denser than hydrogen. This accumulation builds a store which becomes the star's next energy source when its hydrogen supply runs out.

CNO Cycle

Another mechanism is the carbon-nitrogen-oxygen (CNO) cycle present in larger stars, requiring temperatures exceeding 1.6x10^7K. This cycle is a six stage process where carbon acts as a catalyst:

$$^{1}_{1}H + ^{12}_{6}C \rightarrow ^{13}_{7}N$$
$$^{13}_{7}N \rightarrow ^{13}_{6}C + e^{+} + \nu$$
$$^{1}_{1}H + ^{13}_{6}C \rightarrow ^{14}_{7}N$$
$$^{1}_{1}H + ^{14}_{7}N \rightarrow ^{15}_{8}O$$
$$^{15}_{8}O \rightarrow ^{15}_{7}N + e^{+} + \nu$$
$$^{1}_{1}H + ^{15}_{7}N \rightarrow ^{12}_{6}C + ^{4}_{2}He$$

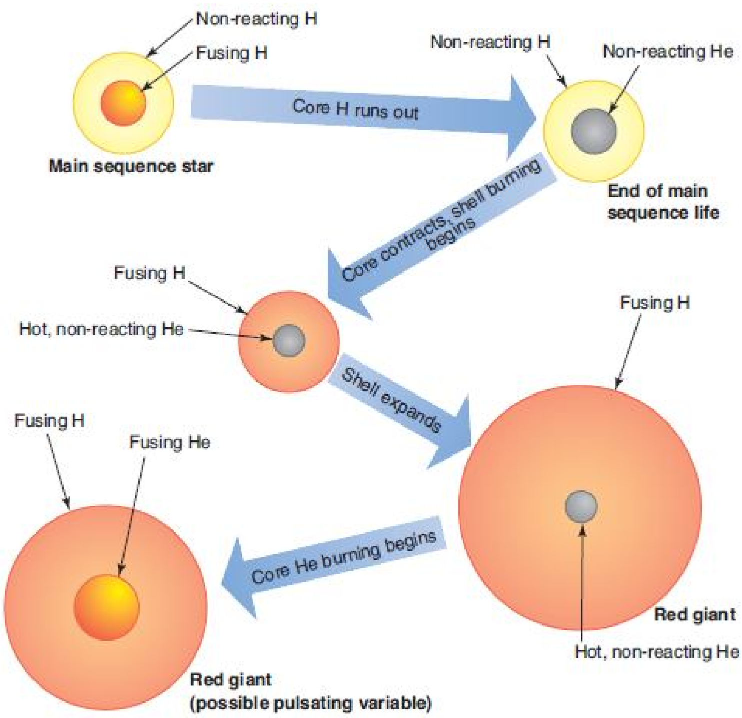
Both p-p chain and CNO cycles can occur simultaneously in a star. In less massive stars, the p-p chain is dominant, while in more massive, hotter stars, the CNO cycle dominates.



Eventually, the star's supply of hydrogen runs out, depending on the mass of the star (i.e. one solar mass - 10 billion years). Lower mass stars have longer lifetimes, while higher mass stars have shorter lifetimes.

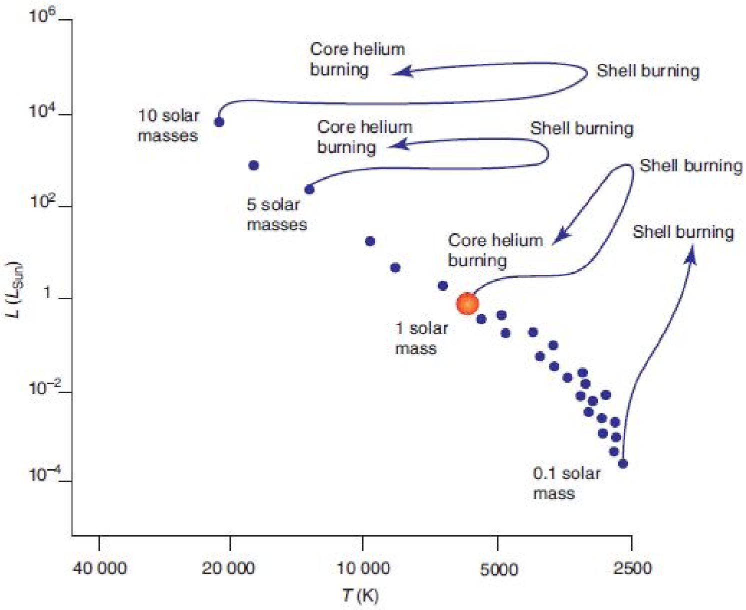
Once the star runs out of hydrogen in its core, the star leaves the main sequence and becomes a red giant.

Red Giant



Red giants are characterised by fusion of helium at its core, surrounded by a hydrogen burning shell. At the end of its main sequence life, a star is surrounded by a shell of unused hydrogen. As there's no radiation pressure to support the core, it contracts under gravity, this contraction heating up the core and the shell surrounding it. Hydrogen fusion to helium begins in the shell, producing energy and increasing luminosity of the star. Due to its own radiation pressure, the shell expands until it's very large and surface temperature is relatively cool. The star is now a red giant, shifted up and to the right from its former position in the H-R diagram.

If a star is less than approximately 0.5 solar masses, it's near the end of its life. Meanwhile, if the star is more than 0.5 solar masses, the non-reacting helium core will reach sufficient temperature to undergo helium fusion. A high mass begins helium fusion very smoothly. But in an intermediate mass star, a **helium flash** occurs, which is the sudden onset of helium fusion in the core of a new red giant. *The star adjusts to the new energy source by reducing its radius and luminosity slightly, moving down and to the left on the H-R diagram, towards the Cepheid instability strip. The hydrogen burning shell can become sufficiently unstable to cause the star to pulsate as a periodic variable, due to changing radiation pressure within.*



Triple Alpha Reaction

In red giants, the fusion of helium in the core proceeds by the triple alpha reaction which is briefly

$$3\,{}^4_2\mathrm{He} \rightarrow {}^{12}_6\mathrm{C} + \gamma$$

This process only produces 10% of the energy per kilogram of fuel compared with hydrogen burning. The fuel is depleted so quickly that as a red giant, a star only spends 10-20% of its prior life as a main sequence star.

Post-Helium burning

With sufficient temperature, the star can also fuse carbon with another helium to form oxygen in order to produce energy.

$${}^{12}_6\mathrm{C} + {}^4_2\mathrm{He} \rightarrow {}^{16}_8\mathrm{O} + \gamma$$

However, after exhausting its supply of helium in the core, fusion reactions cease as the core is largely composed of non-reacting carbon and oxygen, although hydrogen fusion is still ongoing in the outer shell.

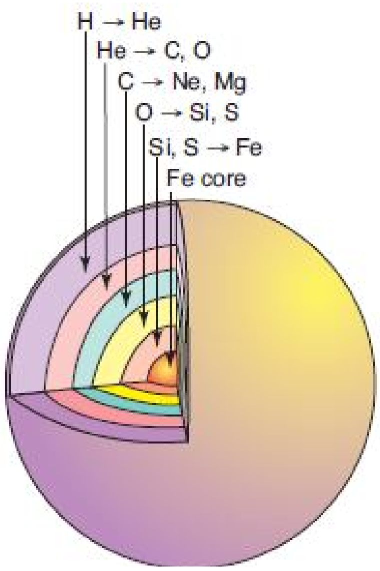
A star of **one solar mass** is nearing the end of its energy producing life, and the still fusing shell expands and becomes unstable, pulsating irregularly and shedding material before its death.

In **larger stars**, the non-reacting carbon core further contracts, heats up, and a helium-burning shell is ignited just below the hydrogen burning shell, causing the star to expand again, moving diagonally up and right on the H-R diagram. *The helium burning shell is unstable and can make the star pulsate as a non-periodic variable*.

In stars **larger than five solar masses**, the temperature of the contracted carbon core is sufficiently hot enough to begin fusion of carbon to neon and magnesium, possibly starting with a **carbon flash**.

When carbon is exhausted, a very massive star may proceed further as each energy source runs out. The **core contracts** under gravity and heats up, igniting the element produced by the shell immediately above it, creating a new shell of energy production. The core contracts, **heating sufficiently** to **ignite** a new, **heavier** energy source. After C--> Ne,Mg are: O--> Si,S; Si,S --> Fe.

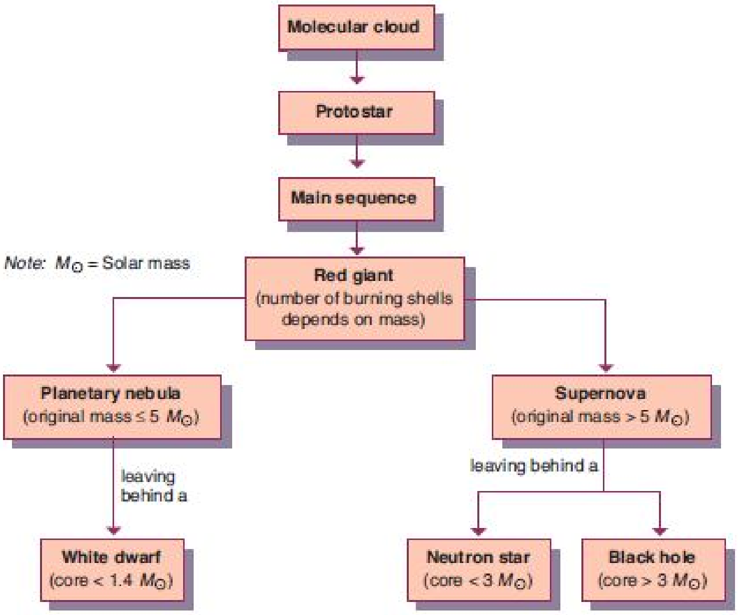
However, with an iron core, fusion reactions must stop as fusion of iron or any heavier element consumes energy, rather than produces it. No matter how massive



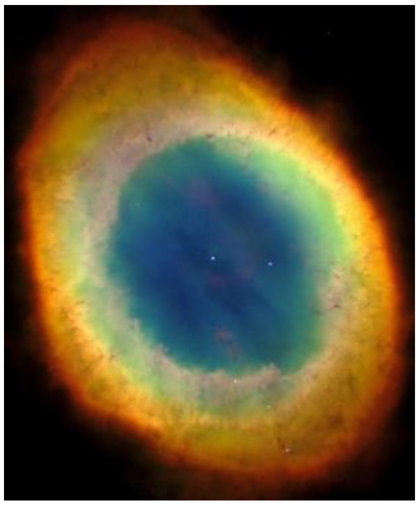
However, with an iron core, fusion reactions must stop as fusion of iron or any heavier element consumes energy, rather than produces it. No matter how massive the star is, eventually it is unable to initiate any new energy source.

Star "Death"

Despite being surrounded by still fusing shells, stars eventually die as it becomes no longer hot enough to fuse its core, (or if it's an iron core that will not fuse to produce energy). From here the star's death follows a similar pattern, as the shells are shed into space, and the core collapses under gravity.



Stars of approximately five solar masses or less



A red giant has a hydrogen burning shell, and if it has sufficiently high mass, it would also eventually have a helium burning shell after fusing helium at the core.

A star of less than five solar masses is not sufficiently hot enough to fuse the core (i.e. of carbon) and the unsupported shells are unstable, producing 'superwinds' and bursts of energy known as **thermal pulses**. These combine to rapidly blow away material from the star, dispersing the shells until only the core is left.

Leaving behind a planetary nebula

Initially, the dispersed material takes the form of an expanding shell shaped nebula around the core, known as a **planetary nebula**.

The core has a mass less than 1.4 solar masses, collapsing under the force of gravity to form a white dwarf. This has high density (10^9kg m^{-3}) and a star the size of our sun would leave behind a white dwarf about the size of the earth. The force of gravity is opposed by electron degeneracy pressure, which stabilizes the star's size.

Eventually, the planetary nebula disperses, and the white dwarf cools to form a black dwarf.

Stars more than five solar masses

Although a massive star can proceed to fuse heavier elements, eventually, it can no longer fuse the core (i.e. Fe will not fuse to produce energy). Hence, the unsupported shells will experience unstable thermal pulses and superwinds similar to less massive stars. However, in a star of more than five solar masses, the core subsequently collapses, drawing in the remaining gases in the shells of the star, and they rebound from this implosion with a **supernova**. This is an explosion of uncontrolled nuclear reactions that blows away materials in the outer layers of the star, leaving behind the highly dense core.

The core left behind is of mass greater than 1.4 solar masses (i.e. exceeding the Chandrasekhar limit), where the force of gravity is sufficient to overcome the electron degeneracy pressure.

A core between 1.4 and 3 solar masses will be crushed such that electrons and protons are forced together into a sea of neutrons, and neutron degeneracy pressure halts the collapse. This is a **neutron star**, which is extremely dense, (density of 10^{17}kg m^{-3}, and just 10 to 15km in diameter.

Due to the conservation of angular momentum, the resulting neutron star from the shrunk core spins 600 revolutions per second. Neutron stars also possess very strong magnetic fields, resulting in the emission of a beam of EM radiation from each magnetic pole. If the Earth happen to be intercepted by one of these beams, we see a regular pulsation of radiation as the beam swings by and these are known as pulsars (with periods ranging from 1.54 milliseconds to 4 seconds).

If the remaining core is greater than 3 solar masses, gravitational force overcomes the neutron degeneracy pressure and nothing can stop its gravitational collapse into a **black hole**. Matter is crushed to a point of infinite density (i.e. singularity), and the gravity is so strong that within a certain radius, the escape velocity exceeds the speed of light. This space is known as the 'event horizon'.

explain how the age of a globular cluster can be determined from its zero-age main sequence plot for a H-R diagram

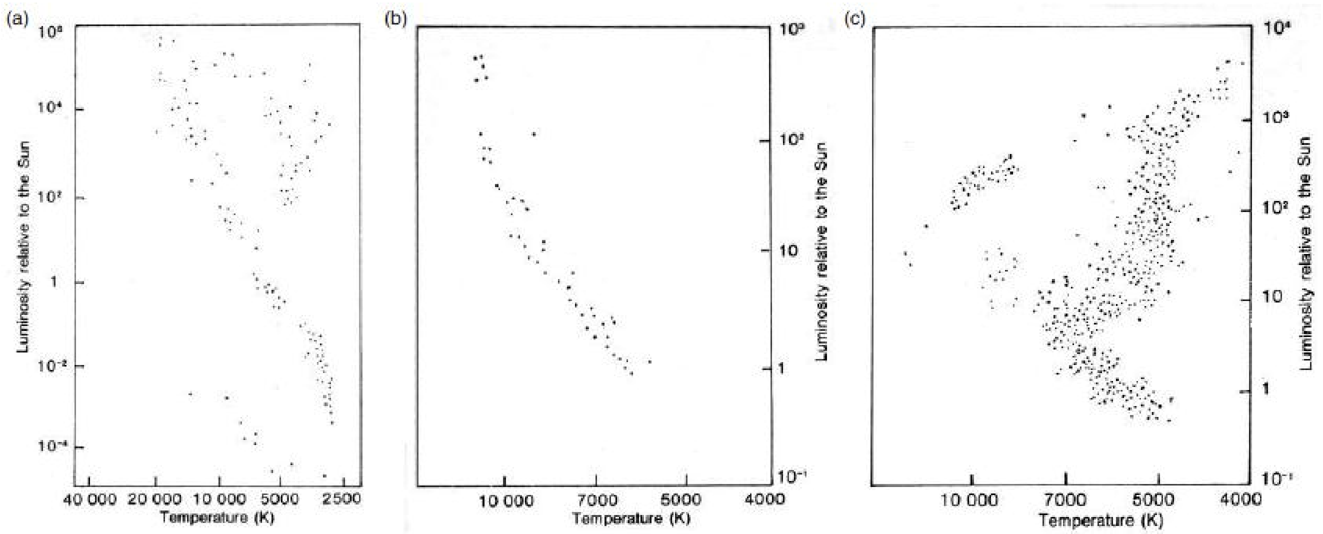
AND

present information by plotting Hertzsprung-Russell diagrams for: nearby or brightest stars, stars in a young open cluster, stars in a globular cluster

Protostars contract out of giant molecular clouds with sufficient mass to form hundreds of thousands of stars. As the spinning cloud contracts, the conservation of angular momentum makes the cloud spin faster, causing it to fragment into smaller spinning parts so that a group of protostars and eventually stars are formed. These stars will be formed in clusters.

There are two distinct types of clusters - open and globular clusters. Globular clusters contain many more stars, however open clusters contain spectral class O and B stars whereas globular clusters don't. These hot, massive stars have short lifetimes, and hence open clusters are younger than globular clusters.

The difference in clusters is revealed in an H-R plot of stars within a cluster.



(a) is a sampling of the nearest and brightest stars, which is a random sampling of star types and each prominent star group is represented.

However, clusters are not a random sample as all the stars within a cluster were formed at much the **same time**, so they are **approximately the same age**.

In (b), stars within an open cluster are catalogued and plotted on an H-R diagram and it's seen that they occupy almost the entire zero-age main sequence.

In (c), stars within globular cluster are plotted, but this time, the top of the main sequence is missing. Instead, there are now stars occupying the red giant region of the H-R diagram, indicating the missing stars have already moved on to become red giants by shifting to the right.

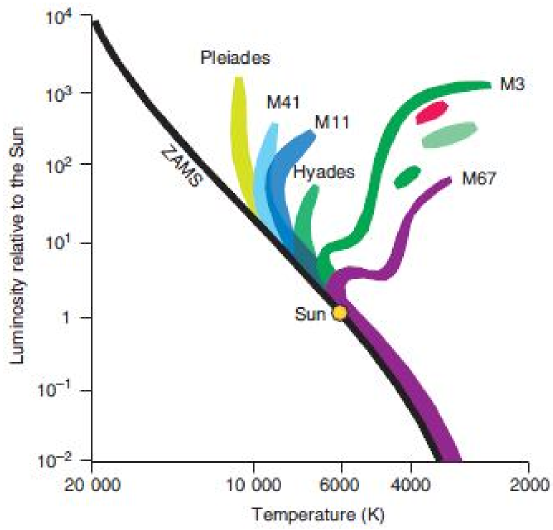
The highest point of the main sequence group on the H-R

The highest point of the main sequence group on the H-R diagram is called the turn off point. When multiple clusters are plotted on the H-R diagram, each cluster shows a different turn-off point and this can be used to infer the age of a cluster.

As a cluster ages, hotter and more massive stars near the top progressively evolve into red giants. This occurs in order of mass, hence the main sequence on the H-R diagram shortens.

The result is that the turn-off point indicates the age of the cluster as hotter, more massive stars have shorter lifetimes and leave the main sequence first.

The oldest clusters are almost as old as the universe (12-15 billion years) while Pleiades is estimated to be just 100 million years old.



present information by plotting on a H-R diagram the pathways of stars of 1, 5 and 10 solar masses during their life cycle

Stars of different masses have characteristics determined by their mass. Hence, stars follow a different pathway during their lifetime and into their death. The figure below plots the movement of stars of approximately 0.1, 1, 5, 10 solar masses. <Incorporate features of each mass from previous dot point>.