Tony Fairall - AST 1000F PART 6
OTHER STARS

The Sun is the only star we can examine close-up and directly see sunspots etc. on its disk. By contrast, all other stars are so distant that they are effectively just pinpoints of light. Their properties have to be found by analysing their light and measuring their positions in the sky very accurately.

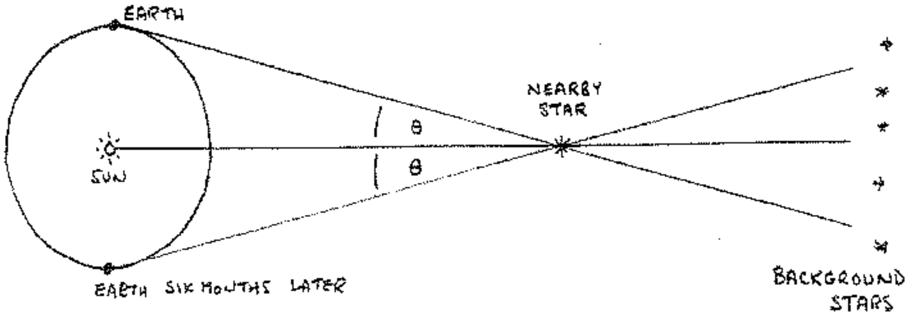
APPARENT MAGNITUDES

Apparent magnitude (already introduced in Exercise 1) is a system used in astronomy to indicate the apparent brightness of a star as seen in the sky. It was devised by Hipparchus (c. 150 B.C.) and in its original form grades stars seen in the sky into six intervals:
The brightest stars in the night sky = 1st magnitude. Progressively fainter - 2nd, 3rd, 4th, 5th magnitude
Faintest stars just visible to the naked eye = 6th magnitude
In more modern times, it was found that this was not a linear scale, but (like hearing) a logarithmic scale when compared with apparent luminosity (measured in energy units) and that 6th magnitude was approximately one hundred times fainter in terms of luminosity than 1st magnitude - i.e. one hundred 6th magnitude stars gives the same amount of light as one 1st magnitude star.
Pogson's rule makes it exactly a difference of 5 magnitudes, for a factor of 100 in luminosity for and allows the scale to be extended:

Difference in magnitude = 2.5 log (ratio of luminosity)

Magnitudes ADD or subtract, while luminosities MULTIPLY or divide. Thus a difference of ten magnitudes (5+5) would correspond to a luminosity ratio of ten thousand times (100 x 100). A difference of fifteen magnitudes (5+5+5) would correspond to a luminosity ratio of a million times (100 x 100 x 100). Nowadays, certain reference stars define the "zero" point of the scale. Modern instrumentation may measure to better than a thousandth of a magnitude. The advent of telescopes has meant that stars fainter than 6th magnitude can be detected. The Space Telescope easily detects stars fainter than m = 26. Negative magnitudes are given to very bright objects; the Sun is about m = -26.
Note that the magnitude scale is not really a measure of brightness, but of faintness. The fainter a star, the numerically higher its magnitude. Apparent magnitude is normally abbreviated 'm' but 'V' (for visual) is often used. Surface brightnesses can, if necessary, be measured in magnitudes per square arc second.

DISTANCES TO STARS - TRIGONOMETRIC PARALLAXES



If you move your head from side to side, objects closer to you appear to 'move' against more distant objects. This parallax technique can be used to find distances of nearby stars. The diameter of the Earth's orbit serves as a baseline
The 'angle of parallax' is

defined as half the angle by which the nearby star appears to move back and forth against the more distant stars. It is measured in arc seconds (1 arc second = 1/3600 of a degree). Distance d can then be measured in units called 'parsecs' where d = 1/(angle of parallax)

1 parsec = 3,08 x 10**13km = 3.26 light years

For larger distances, Kiloparsecs (1000 pc) and Megaparsecs (1000 000 pc) are used.

In practice, the angles of parallax are extremely small and very difficult to measure; even for the nearest stellar system (Alpha Centauri), the angle is only 0.75 arc seconds. Adding to the difficulties are transverse motions of stars (Proper Motion - see below), an annual displacement of the star's position due to the 'aberration' of light (due to the Earth's motion around the Sun, and not its position) and whether the background stars are really much more distant. To establish angles of parallax, it is normally necessary to observe a star (at six month intervals) over several years. Even so, one can at best measure distances out to a few hundred parsecs. Obviously, the uncertainties increase with distance.

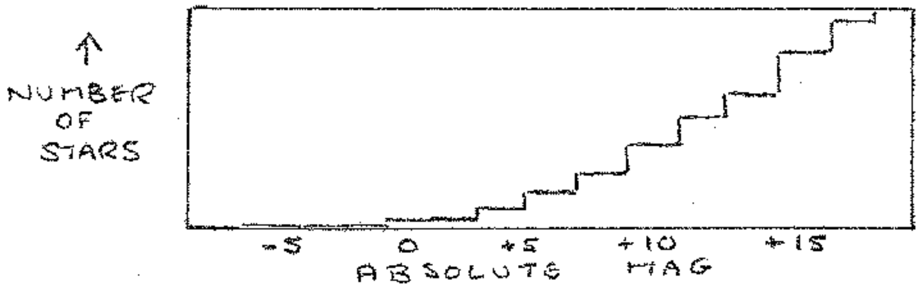
Historically, unsuccessful attempt to measure parallaxes were made in the 18th century. The first successful measurement of parallax - of Alpha Centauri - was made by Thomas Henderson here at the Cape around 1830, but his results were only published after those of the German astronomer Bessell, who successfully (and more accurately) measured a northern star.

In recent years, a very major improvement in the accuracy of measured parallaxes was achieved by the Hipparcos satellite, which observed from space. Even so accurate parallaxes are still only available over to some 200 pc or so (several hundred light years).

LUMINOSITIES OF STARS - ABSOLUTE MAGNITUDE

Once both the apparent magnitude and the distance of a star are known, its True intrinsic luminosity can be determined. Magnitude units can again be used.

M = Absolute magnitude = apparent magnitude if the star were viewed at a standard distance of 10 parsecs.



It can be derived from the apparent magnitude m and distance d according to the formula,

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

Our Sun has an absolute magnitude of about M = +5. But stars exhibit an enormous range in luminosity. The most luminous stars are approaching a million times brighter than our Sun (i.e. M = -10). The least luminous stars may be fainter than one ten thousandth of our Sun's luminosity (fainter than M = 15). Remember the magnitude scales really measure how dim a star is, rather than how bright it is; the dimmer the star, the numerically higher its magnitude.

A typical stellar population has many more faint stars than bright ones. Our Sun is brighter than average.

DISTANCE MODULUS

Since the difference between apparent and absolute magnitude depends only on distance.

m - M is called the distance modulus
$m - M = 5 \log d - 5$
Distance modulus is positive for distances greater than 10 pc (the usual case).
A cluster of stars has the advantage that all its members are at roughly the same distance from us. Its distance modulus is constant. Thus, while its member stars may exhibit a range in apparent magnitude, the range would be the
same in absolute magnitude - because the difference apparent to absolute magnitudes is constant.

TRANSVERSE MOTIONS OF STARS - PROPER MOTIONS

Although the patterns of stars in the sky appear fixed, the stars are nevertheless moving, though the apparent motions are very small. The 'proper motion' is the apparent motion across the sky (after parallax and aberration are taken into account) expressed in arc seconds per year. It can be converted into a tangential velocity via
Transverse speed (in km/s) = 4.74 X (proper motion (in arc seconds per year) X d
The direction of the proper motion can also be noted.

RADIAL VELOCITIES OF STARS

Due to the Doppler effect (well-known in Physics), stars moving towards us have their spectral features blueshifted; stars moving away have spectral features redshifted. By measuring the size of these shifts, accurate radial speeds (in km/sec) can be determined from a single observation.

MOTIONS OF STARS AND OF THE SUN

Transverse and radial speeds of stars can be combined to obtain the true speed. Most nearby stars show speeds in the region of 0 to 40 km s-1, but a few rare "high-velocity" stars have speeds over 100 km s-1. Obviously directions of motion can be obtained via the direction of the proper motions. All these motions are of course relative to our Sun and its Solar System and it is possible, by statistical techniques, to extract the apparent 'local, motion of the Sun (relative to its companion stars) - over and above its circular velocity around the centre of the galaxy. The Sun's motion can also be used for "statistical parallaxes" by generating a much longer baseline than the diameter of the orbit of the Earth.

SURFACE TEMPERATURES OF STARS

The dominant radiation from stars is light, so their surface temperatures must be thousands of degrees. If one could measure where the wavelength peaked, then the temperature could be found from the laws of physics. However, one simple technique is to compare apparent magnitudes in two different colours:

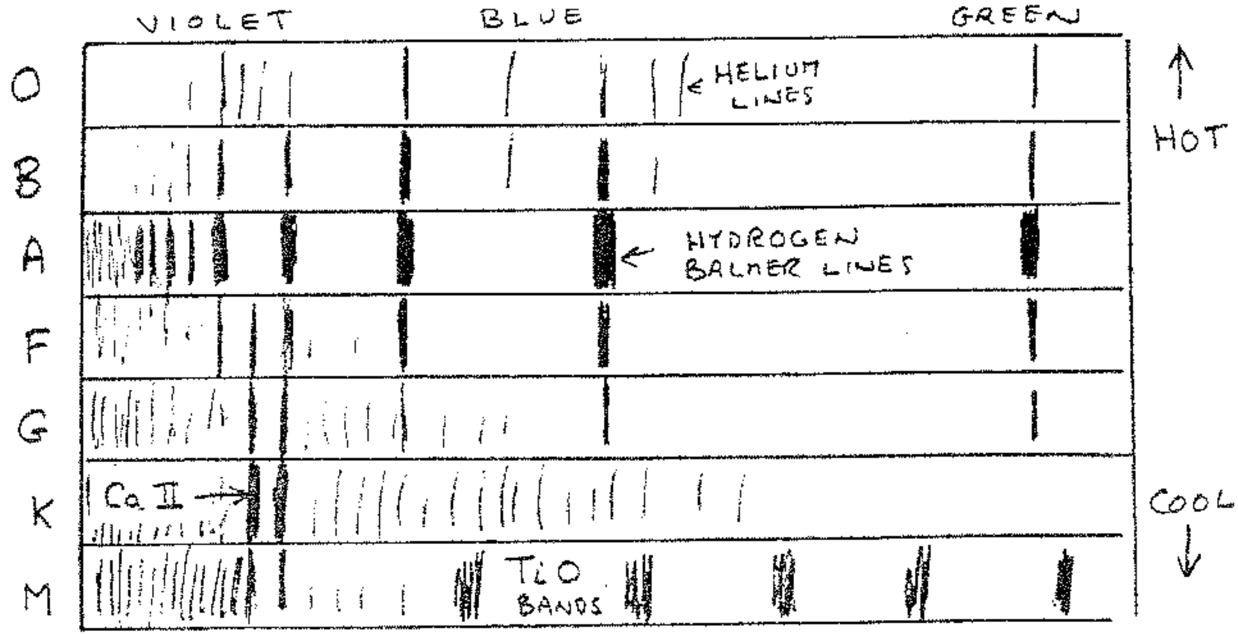
Let B = apparent magnitude measured through a standard blue filter
V = apparent magnitude through a yellow (visual) filter.
Then 'Colour' = B-V

Roughly B-V = 2.0	Temperature = 2000K
B-V = 0.6	Temperature = 5500K (like our Sun)
B-V = 0.0	Temperature = 10000K
B-V = -0.35	Temperature = 50000K

(B-V approaches -0.4 as temperature tends to infinity)

SPECTRA OF STARS

The visible bright surface of a star (like the disk of our Sun) is formed by dense gas. It radiates a continuous spectrum of colours. However, above the 'surface', the cooler gas (the 'atmosphere') acts to superpose dark lines on the spectrum. The patterns of dark lines differ from star to star, and seven main classes have been recognised (see diagram).



The Sequence can be remembered by "Oh, be a fine girl, kiss me".

Expert eyes can discriminate to a tenth of a spectral class - hence subdivisions as per ....A8,A9,FO,F1,F2... .F9,GO,GI,G2

Our Sun 1.S a G2 star.

The sequence has been found to represent decreasing surface temperature - An AO star, temperature 10 000 K, has B-V = 0.0.

Whilst the gross difference in spectra is due to surface temperature, ~ experienced investigators can also discriminate a luminosity class (larger, more luminous stars have lower pressure in their atmospheres and sharper ~ lines) and abundance differences (relative proportions of the chemical elements).

SIZES OF THE STARS

Since the stars appear as pinpoints, we use the laws of physics to determine their sizes as follows

(Total luminosity = (Luminosity per X (Surface Area in
of star) square metre) square metres)

The term on the left is represented by the absolute magnitude. The first term on the right depends on the fourth power of the surface temperature (Stephan-Boltzmann law). Thus if the absolute magnitude and surface temperature of a star is known, its surface area and hence its size can be derived.

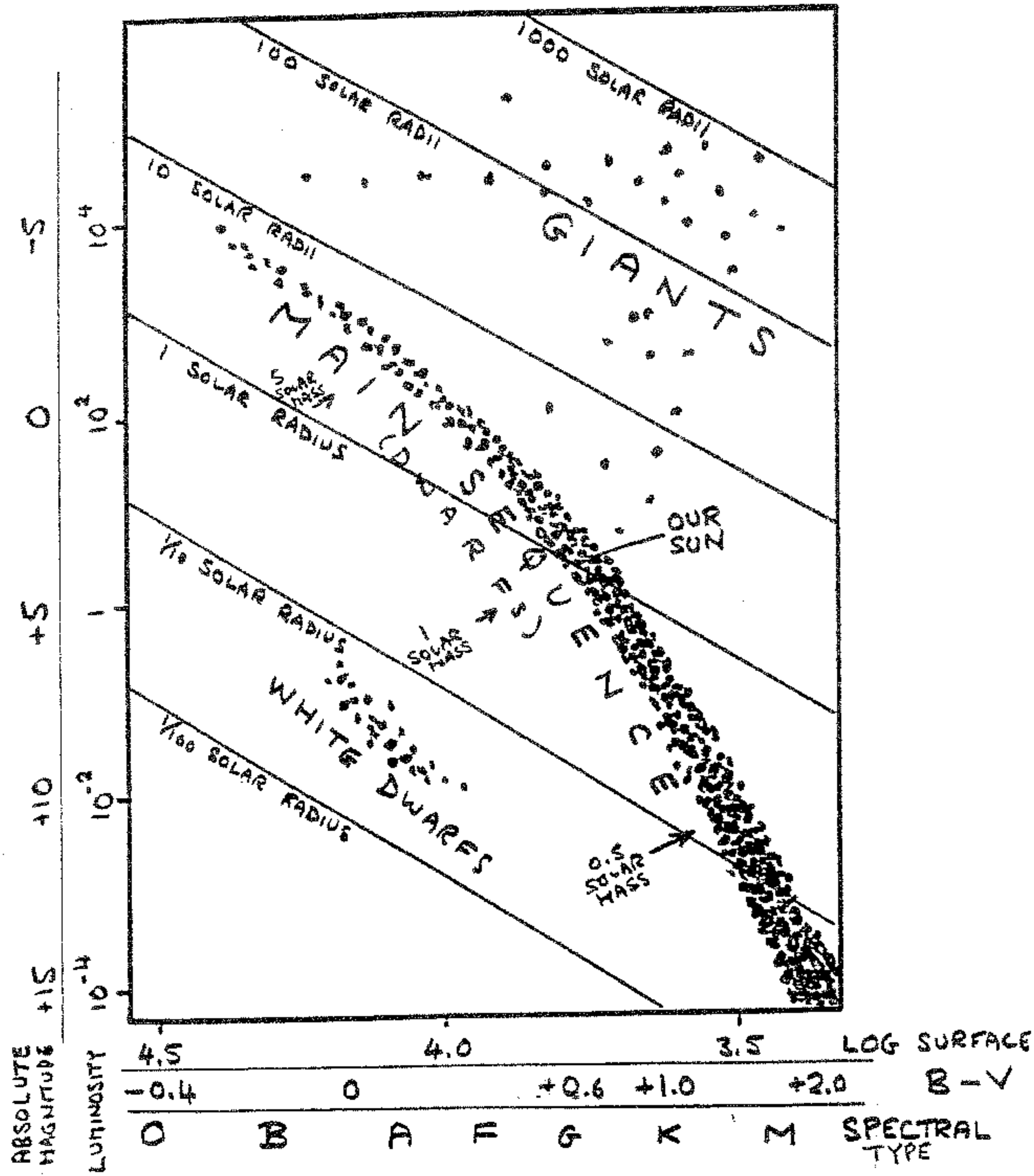
This reveals remarkable variations in sizes. The smallest stars (white dwarfs) are just over 1% of our Sun's diameter, the biggest (red giants) are nearly a thousand times the Sun's ~ diameter.

MASSES OF STARS

The most difficult parameter of a star to measure is its mass. Only if it exhibits orbital motion (around another star, or has a body in orbit moving around it, is it possible to determine its mass.

HERTZSPRUNG-RUSSELL DIAGRAM

Almost all the properties so far discussed can be combined in a single diagram:



This is the most important diagram in stellar astronomy - it shows a correlation between the luminosities and surface temperatures and thereby classifies stars as either Main Sequence (Dwarfs), Giants or White Dwarfs - each representing a major stage in stellar evolution (Roughly 90% of stars are Main Sequence, 1% are Giants and 10% are White Dwarfs).

Note first that all the scales involved are logarithmic ones, so the diagram encompasses a very wide range of luminosities, temperatures and radii.

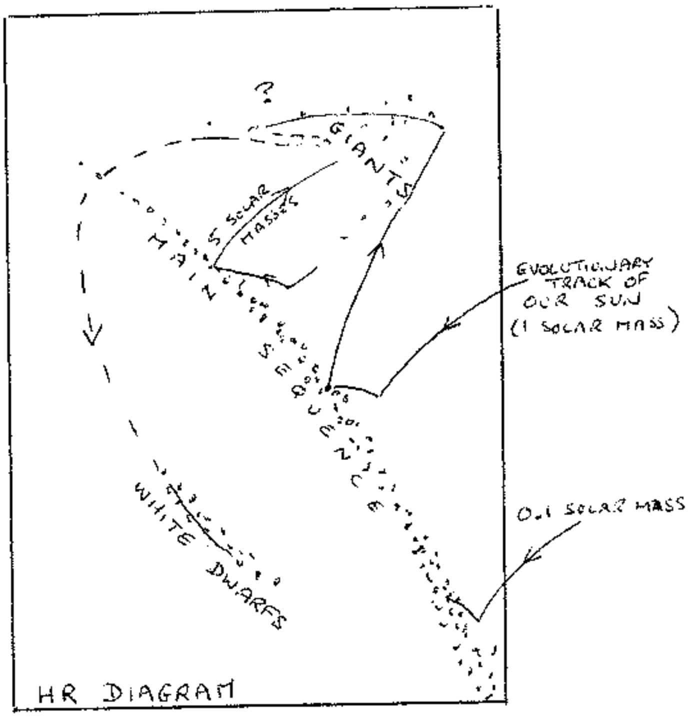
The vertical scale is luminosity - the stars at the top are the most luminous, those at the bottom are the least luminous. Luminosity can be expressed either by absolute magnitude (already a log scale) or in terms of luminosity compared to our Sun. The stars at the top are about a million times more luminous than our Sun, those at the bottom only about one ten thousandth the Sun's luminosity.

By tradition, the sense of the horizontal axis is reversed; stars with the highest surface temperatures lie towards the left, those with the lowest surface temperature to the right. The ordinate is actually the log of the surface temperature, but it is more conveniently measured by either Colour (B- V) or Spectral type.

As above, sizes of stars can be found from their total luminosity (vertical scale) and their surface temperature (horizontal scale). The outcome is a set of slanted lines showing stars of equal size. Thus the biggest stars may have nearly a thousand times the radius of our Sun, while the Small White Dwarfs are not much bigger than the Earth.

EVOLUTIONARY TRACKS

In the previous chapter, the formation, lifetime and demise of our Sun was described. The evolution of our nearest star can be shown as a track on the HR diagram.



The general scenario described for our Sun can be applied to any star; the only differences will be described below.
The 'main sequence' lifetime of a star, where the star holds a constant luminosity, size and surface temperature and a fixed position on the HR diagram, is the stable 'hydrogen burning' phase described in the preceding chapter. The main sequence is created by variations in the masses of stars. Stars with highest mass lie towards the top, stars with lowest mass towards the bottom.
The most-massive stars possible are probably 50-100 solar masses (a solar mass is the mass of our Sun); stars with more mass than that would rapidly destroy themselves by runaway nuclear reactions. The least-massive stars possible are
probably about 0.1 solar masses or slightly less; bodies less massive still would not produce hot enough cores to initiate nuclear reactions - instead they would become planets.
Brown dwarfs are borderline objects – barely glowing. Some may even be 'deuterium burning' which would only have a very short lifetime.

VARIATIONS IN THE MAIN SEQUENCE LIFETIME

While stars exhibit a tremendous variation in luminosity, their variation in mass is far less. That implies that the rate of burning hydrogen fuel varies far more than the reserves of such fuel. Some stars have extremely short lifetimes (less than a million years). Other last far far longer than the current age of the Universe.

Mass of Star Approx.	Main Sequence Lifetime
>100 Solar masses	(Runaway nuclear reaction destroy star)
50 Solar masses	5 million years
10 Solar masses	100 million years
1 Solar mass	10 billion years
0.5 Solar mass	50 billion years
0.1 Solar mass	1 000 billion years
<0.1 Solar mass	(Do not achieve stardom)

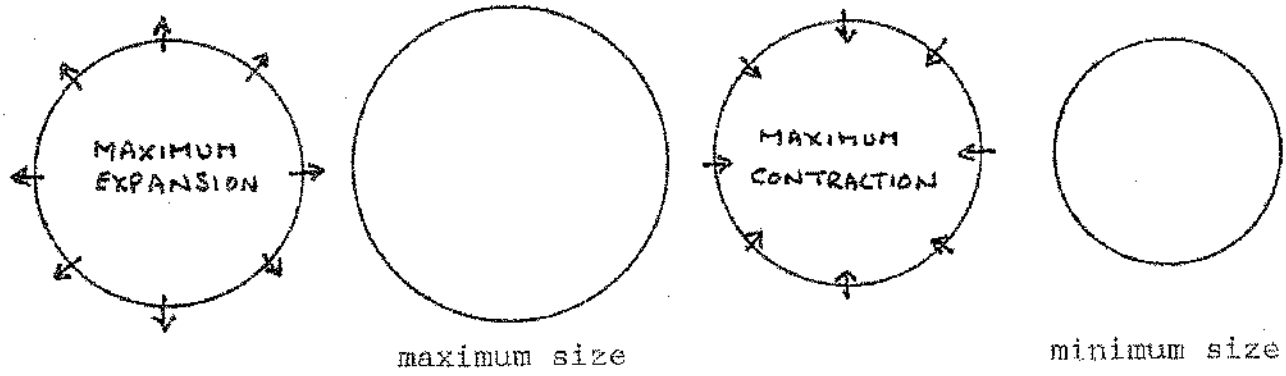
By comparison, the age of the universe is about 14 billion years, insufficient time for the low-mass stars to have evolved off the main sequence.

STELLAR REMNANTS

Provided the core of a star does not exceed 1.3 solar masses, it will finally become a white dwarf star, as described for our Sun. If the core mass is greater than 1.3 solar masses, it will collapse to an even denser state, a neutron star.
A neutron star is like a giant atomic nucleus with a diameter of only about 10 km and the density 10**13 times that of water! To gauge what this means, imagine a teaspoon of a material that weighs several million tons!
(This is simply the density of atomic nuclei - like those in your body. Almost all the mass of an atom is concentrated into the tiny atomic nucleus in its centre. The rest of the atom - the electron cloud - is virtually empty space. Our bodies are almost entirely empty space!)
If the core exceeds 3.2 solar masses, it may contract even beyond a neutron star to form a black hole. A black hole is effectively a mass singularity, from which not even light can escape.

PULSATING VARIABLE STARS

In general, the size of a star is dictated by the balance between gravity trying to shrink the star and gas pressure trying to make the star expand outwards. Normally, as with our Sun, the two are perfectly in balance and the size remains unchanged for millions of years. However, in certain regions of the HR diagram, a star may be susceptible - to radial oscillations - inward and outward about the equilibrium position (like a weight hung on a spring that oscillates). Thus the star pulsates in and out.

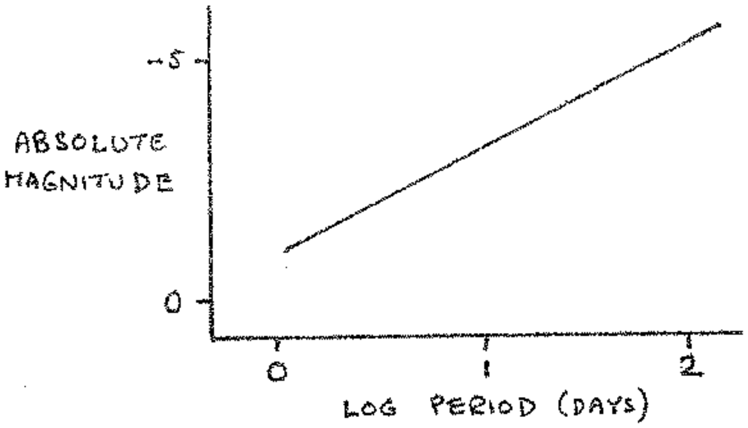


The size of the star, and its surface temperature, vary. This will affect that star's output of light - although usually maximum light output corresponds to maximum expansion (maximum surface temperature but not maximum size) while minimum output corresponds to maximum contraction (minimum surface temperature but not minimum size).

The period of the pulsation varies with the size of the star. Stars around the size of our Sun would oscillate once in about an hour, whereas giant stars might take days, tens of days, or even hundreds of days (in the case of Red Giants).

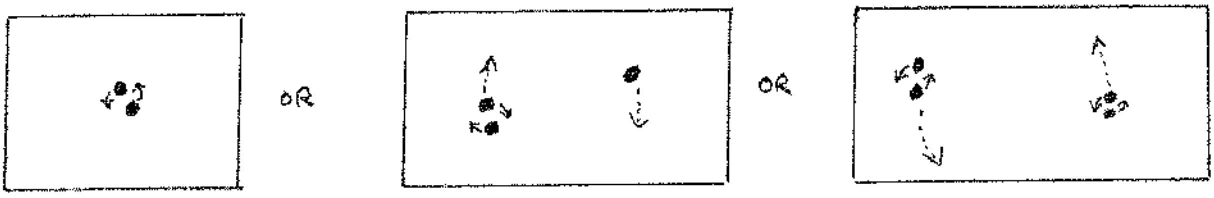
CEPHEID VARIABLE STARS AS DISTANCE INDICATORS

One type of pulsating star turns out to be extremely useful in astronomy. Cepheid variables are giant highly luminous stars that have periods from 2 to 45 days. There is a well defined relationship between period and absolute magnitude (see diagram).



It is relatively easy to identify Cepheids - even in galaxies outside of our own - and to measure their periods. This gives their absolute magnitudes. If the apparent magnitudes are measured, then their distances can be determined by the formula given earlier in this chapter. It was by using Cepheids that Edwin Hubble proved that the Great Galaxy in Andromeda really was a separate 'Island Universe' to our own galaxy. In more modern times, the design of the Hubble Space Telescope was such for it to detect Cepheid variable stars in galaxies in the Virgo cluster - thereby allowing it to refine the distance scale for the entire universe.

VISUAL BINARY STARS



Many stars, though they appear as single pinpoints of light to the naked eye, are resolved as double stars when viewed through the telescope. Over time, the stars may be seen orbiting about each other. As mentioned earlier, these are the only cases where masses can be determined.
In general, these visual binaries are stars separated by tens of Astronomical units, which may take tens of years to orbit each other.
Some star systems may have three or more members. For stability, the stars will "pair" up, like binary stars:
It is only possible to determine masses of stars in double star systems. If ml and m2 are the masses of the two stars (expressed in solar masses), A is their mean separation (in astronomical units), and P is the period of revolution in years, then

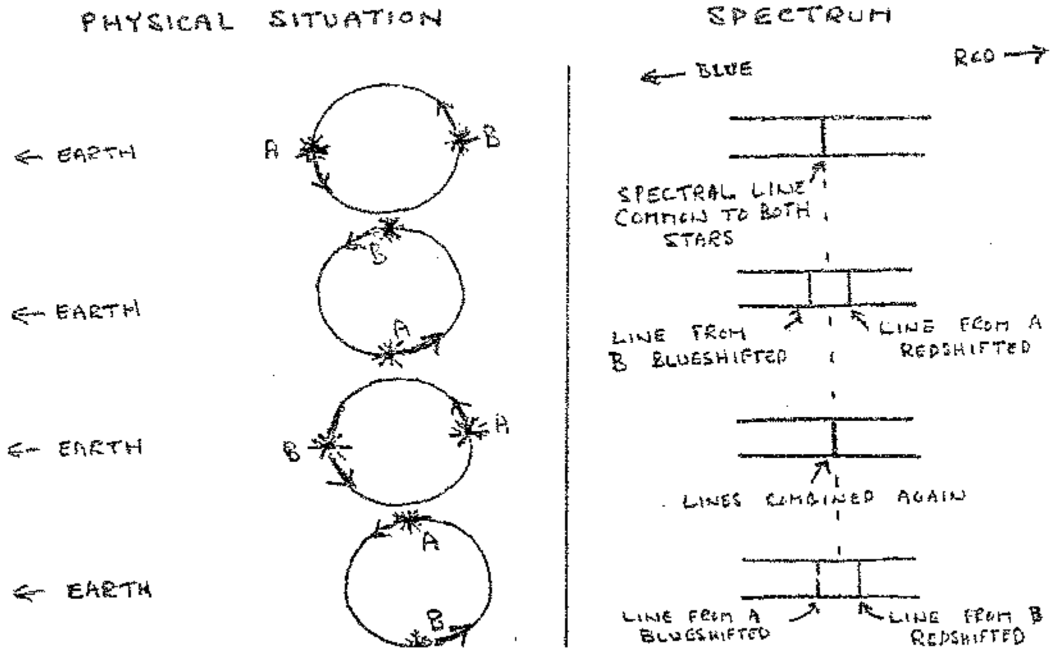
ml + mz = A**3/P**2

There are difficulties in determining A - the true, not projected, separation - and whatever uncertainty in the distance is reflected in A. Since A is entered as a cube, slight errors are magnified. Finally the combined, not the individual masses, is obtained.

SPECTROSCOPIC BINARY STARS

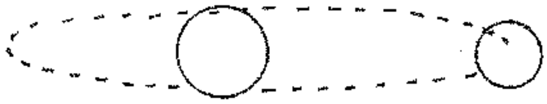
There are many stars much closer together - but too close to be seen as visual binaries. When the stars are very close to one another they may orbit each other in only a few days or less and their orbital velocities may be tens of kilometres per second. This allows us to discern their binary nature by the Doppler Effect, even though we never see them as two stars.

It depends on the orbits of the stars being seen towards edge-on. At a particular time, one star will be moving towards us and its spectral lines will be slightly blueshifted. At the same time, its companion star will be moving away from us and its spectral lines redshifted. The full cycle of the orbit can be followed as suggested in the diagram on the previous page.



ECLIPSING BINARY STARS

A few spectroscopic binary star orbits are seen almost exactly edge on - so that the stars actually eclipse each other (see diagram).



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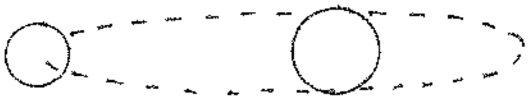

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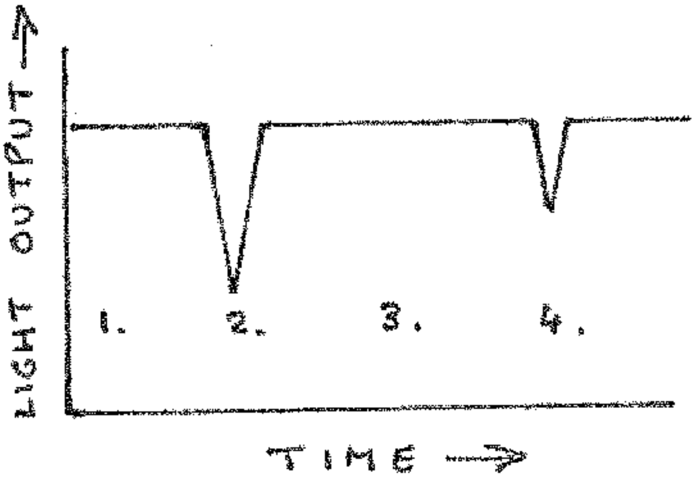
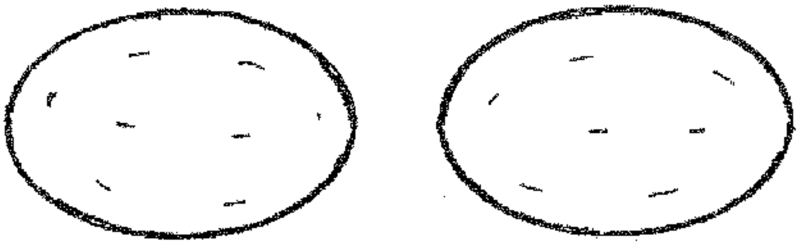
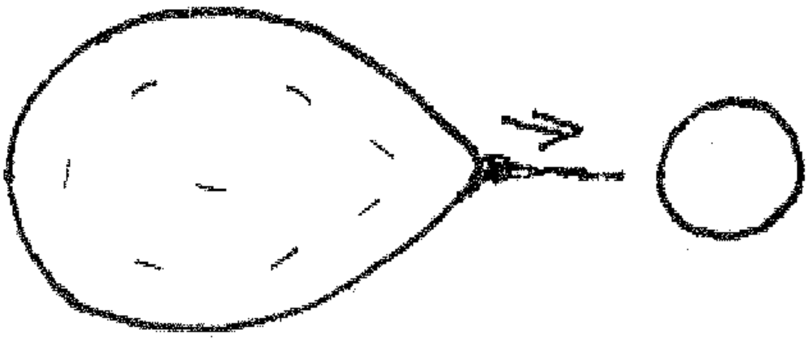


BINARY STARS EXTREMELY CLOSE TOGETHER

There are some cases where two stars are very close to one another and orbit about each other in two or three hours. So close are the stars that their shapes are no longer spherical.



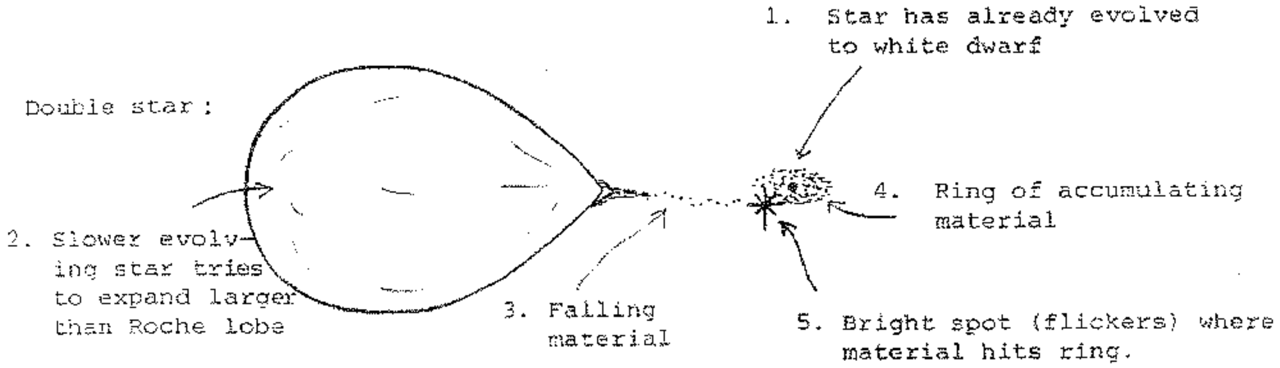
Should the separation decrease further, or one of the stars expand (due to evolution at the end of its main sequence lifetime), then material may flow from one star to another.



In some cases, the companion star may already be a white dwarf or neutron stars. Such systems are believed responsible for NOVA outbursts or X-RAY binaries.

NOVA OUTBURSTS

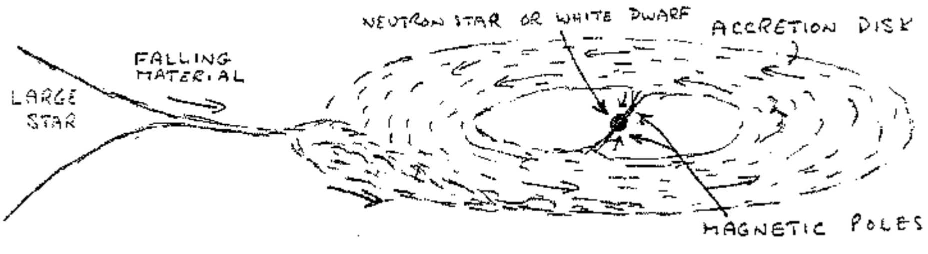
'Nova' means new, as that it what it may seem like in the sky, but these are rather existing stars undergoing cataclysmic outbursts causing a sudden and large increase in luminosity.



System believed responsible – see diagram above.

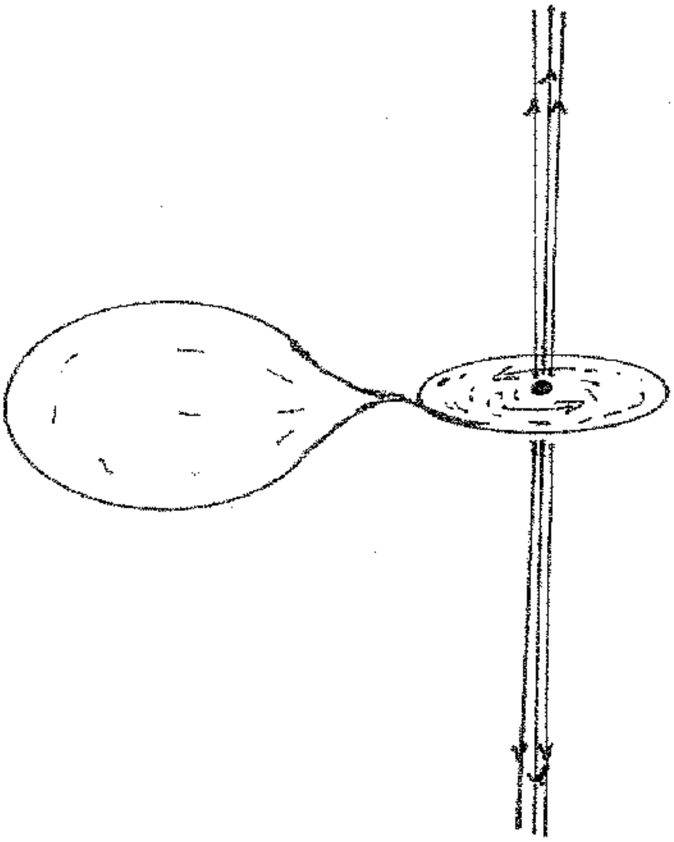
The material in the ring builds up to a critical situation when a thermonuclear runaway occurs and the ring material is blown off causing the nova outburst. The two stars survive and the process repeats. 'Dwarf' novae ~ usually have milder, more frequent outbursts.

X-RAY BINARIES



Numerous galactic X-ray sources are thought to arise from binary ; systems similar to that just described. The energy source for the X-rays is believed to be derived from material

falling to the surface of a neutron star or white dwarf. Close to the compact companion, the material is thought to be guided by the companion's strong magnetic field.
The sudden deceleration, just above the surface, is the source of X-ray emission.
Complications may occur. In some cases, a mechanism seems to act to hold back the infalling material until it breaks through in an avalanche - so called 'X-ray Bursters'. Also magnetic fields may be caught and compressed in the disk then twisted up violently by increasing rotation. This may lead to tremendous electrical potentials, possibly responsible for driving off part of the infalling material in two jets (perpendicular to the disk). The star SS 433 may be an extreme case - the velocity of material in the jets being ~25% of the speed of light.



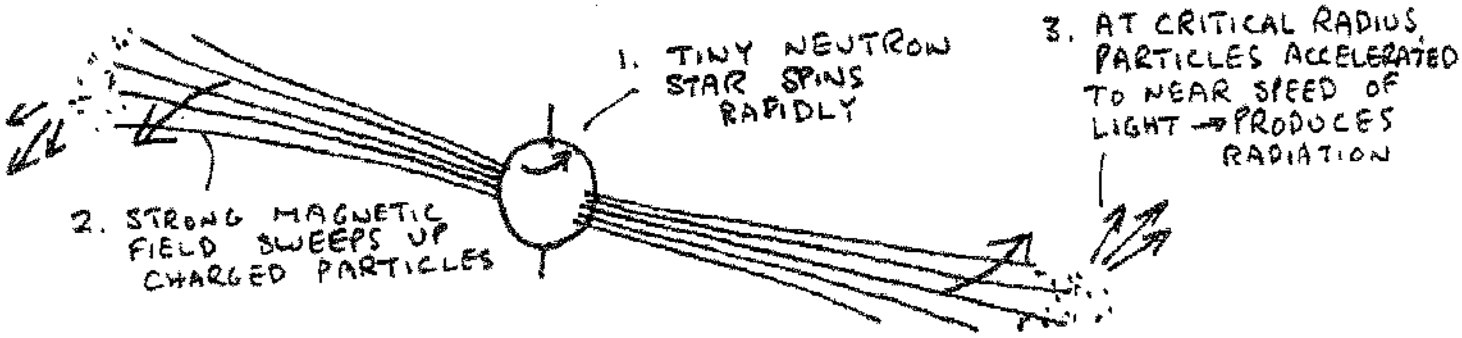
SUPERNOVAS

Certain stars suffer catastrophic SUPERNOVA explosions. These are rare events - only a handful are known to have occurred in our galaxy throughout recorded history, but hundreds are discovered per year in distant galaxies. In 1987, a supernova was seen to explode in the Large Magellanic Cloud. At its brightest it appeared at apparent magnitude = 3, the first recorded naked-eye supernova since 1604. The explosion is probably preceded by a catastrophic collapse of the core of the star. The core itself becomes a neutron star; the remainder of the star collapses to a great density, then rebounds as an explosively expanding mass - moving outwards at speeds of thousands of kilometres per second. As this explosion grows in size and surface area, its luminosity may become millions of times greater than that of our Sun. Radioactive elements may continue to power the remnant, but after weeks (or two months in the case of 1987 supernova) it begins to fade.
Two basic sorts of supernovae are identified. Type I are the more luminous but their remnants are relatively low mass. They are believed to result from the collapse of a white dwarf to a neutron star in a binary system, where matter transferred to the white dwarf has taken it over a critical 1.3 solar mass limit. A sub type – Type Ia – has proved to be a useful distance indicator on cosmological scales (thanks to their incredible brightness).

Type II supernova, like the one in the Large Magellanic Cloud, seem to eject higher mass and probably produce more conspicuous remnants, the most famous of which is the Crab Nebula (Remnant of the 1054 A.D. supernova, seen in the constellation of Taurus).

PULSARS

A pulsar is believed to be a rapidly spinning neutron star with a very intense magnetic field, apparently formed from the implosion of the core of the supernova star. Both angular momentum and the magnetic field have been conserved but the physical dimensions reduced drastically! The rotational axis and the magnetic axis do not coincide:



The exact mecnanism is not understood, but the outcome is that the object shines out two beams - like a lighthouse. Thus, as the object spins, observers see pulses of radiation (usually only in radio region) just as one would see a 'pulse' of light from a lighthouse.

The most famous pulsar is that in the Crab Nebula. Since it is so young, it spins in only 1/30 sec and its pulses are detected in X-ray, visible and radio wavelengths. Furthermore it appears to supply relativistic charged particles into the surrounding remnant which spiral in its magnetic field to produce optical 'synchrotron' radiation.

The Crab pulsar is gradually slowing down - its energy source is its rotation. Eventually it will spin only once in a second and emit only radio pulses, as do most other pulsars. Presumably all pulsars reach a stage where even their radio pulses fade and they are no longer detectable.

On the other hand, pulsars with periods which are only slightly greater than a millisecond have been detected. These ultra-fast rotators are probably members of binary systems and have been 'spun-up' by infalling material from the companion star.