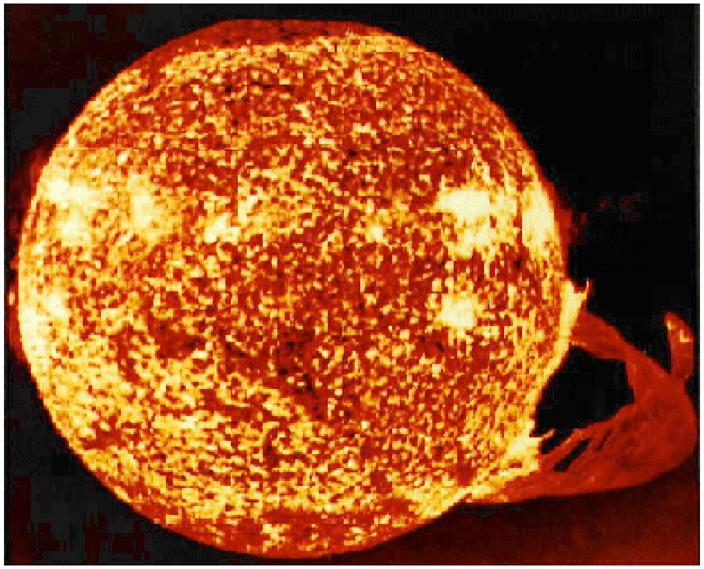
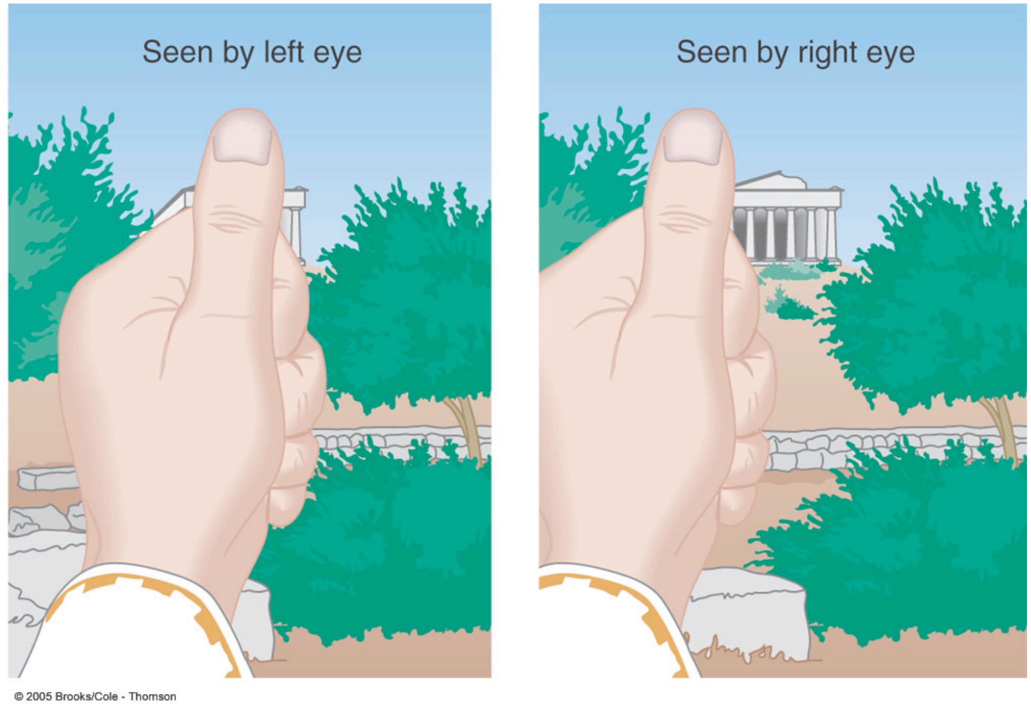
The Family of Stars

What is a star? How far away are they? How hot are they? How large are they? How much do they weigh?



The only star that we can study in detail is the sun. Every other star appears as a pinprick of light; even our closest neighbour is 40 trillion km away! But the Sun is just one of millions of stars in our galaxy, the Milky Way. In this chapter, we'll see how we can study these stars despite their great distances and learn a lot about the family of stars in our Milky Way and beyond.

Distances to nearby stars can be measured by using parallax. The idea behind parallax is that a distance object's position appears slightly different when viewed from different vantage points.

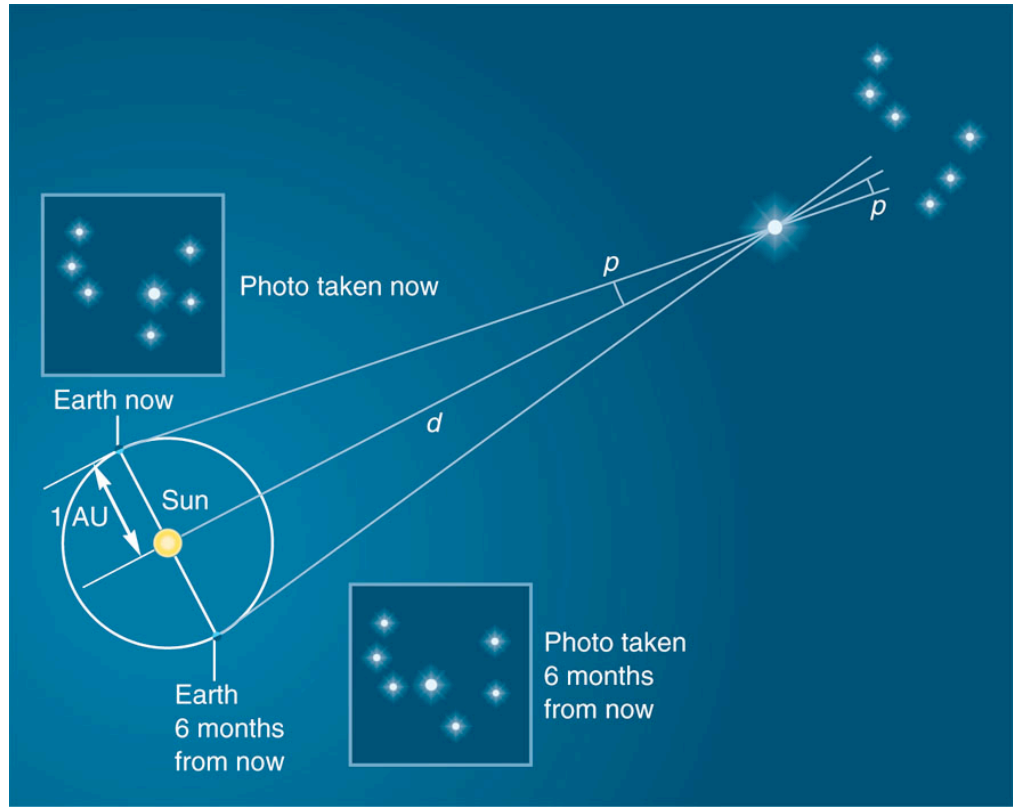


For example, the temple in this cartoon appears to be in a different place relative to the thumb depending on whether it is viewed by the right eye or the left.

Stellar parallax is seen when a nearby star seems to change its position (relative the the "fixed" background of distant stars) as the earth moves around its orbit.

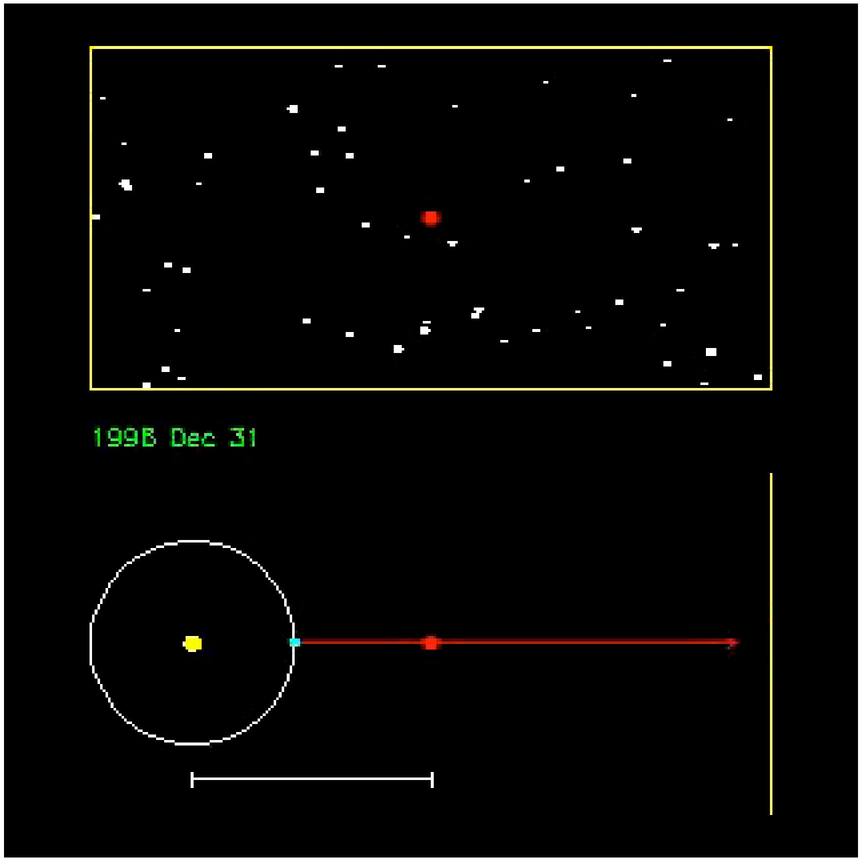
The angle of parallax, p, is half the angle that a star appears to move in a 6 month period.

Using parallax, we can define a new unit of distance that is more convenient than light years, km or AU.



1 parsec is the distance to a star whose angle of parallax is 1 second of arc. A larger parallax angle therefore means the star is closer.

This movie shows the apparent position of a red star as seen from the earth during the year. The red line shows our sightline to the star and the top panel shows it relative to the background of stars.

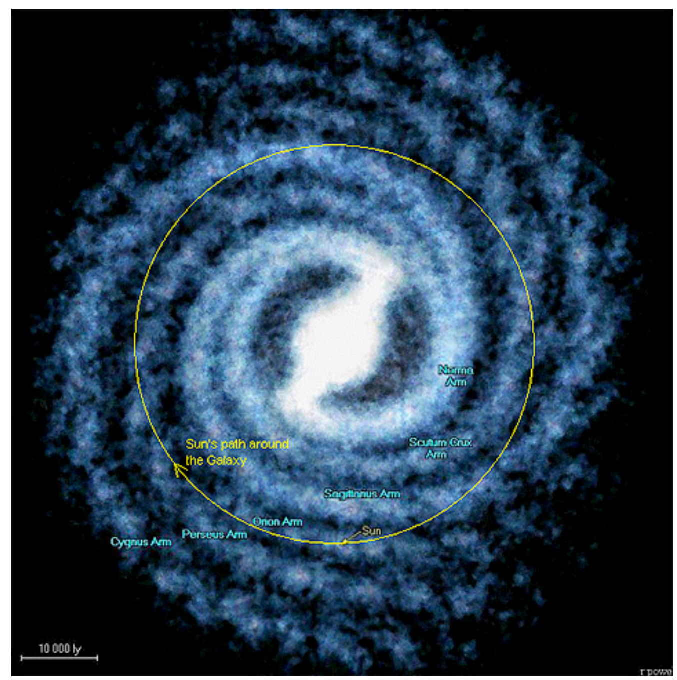


Parsecs make it easy to determine the distance to a star if you know the angle of parallax, p:

$$d\ (\text{pc}) = 1\ /\ p\ (\text{arcsecs})$$

1 parsec (pc) is equal to 206, 265 AU or 3.26 lightyears, or 3×10^{13} km. We also use kilo parsecs (kpc) for larger distances, where 1 kpc = 1000 pc. Which units would be most appropriate for the following:

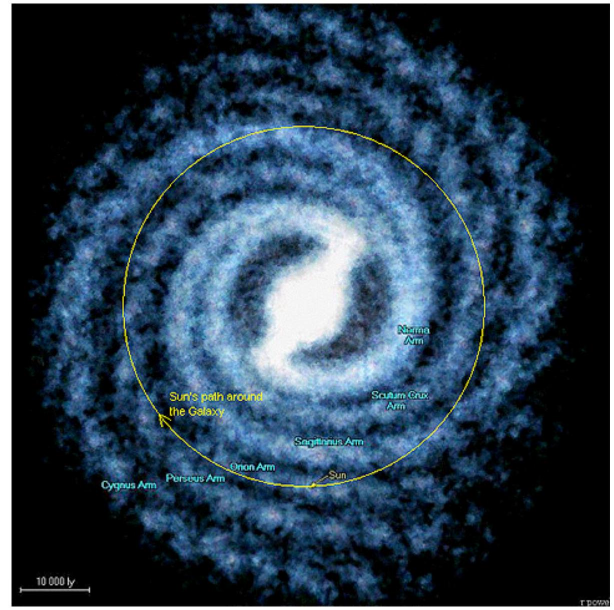
- The size of your house
- The diameter of the moon
- The distance to Mars
- The distance to the nearest stars?
- The size of our galaxy?



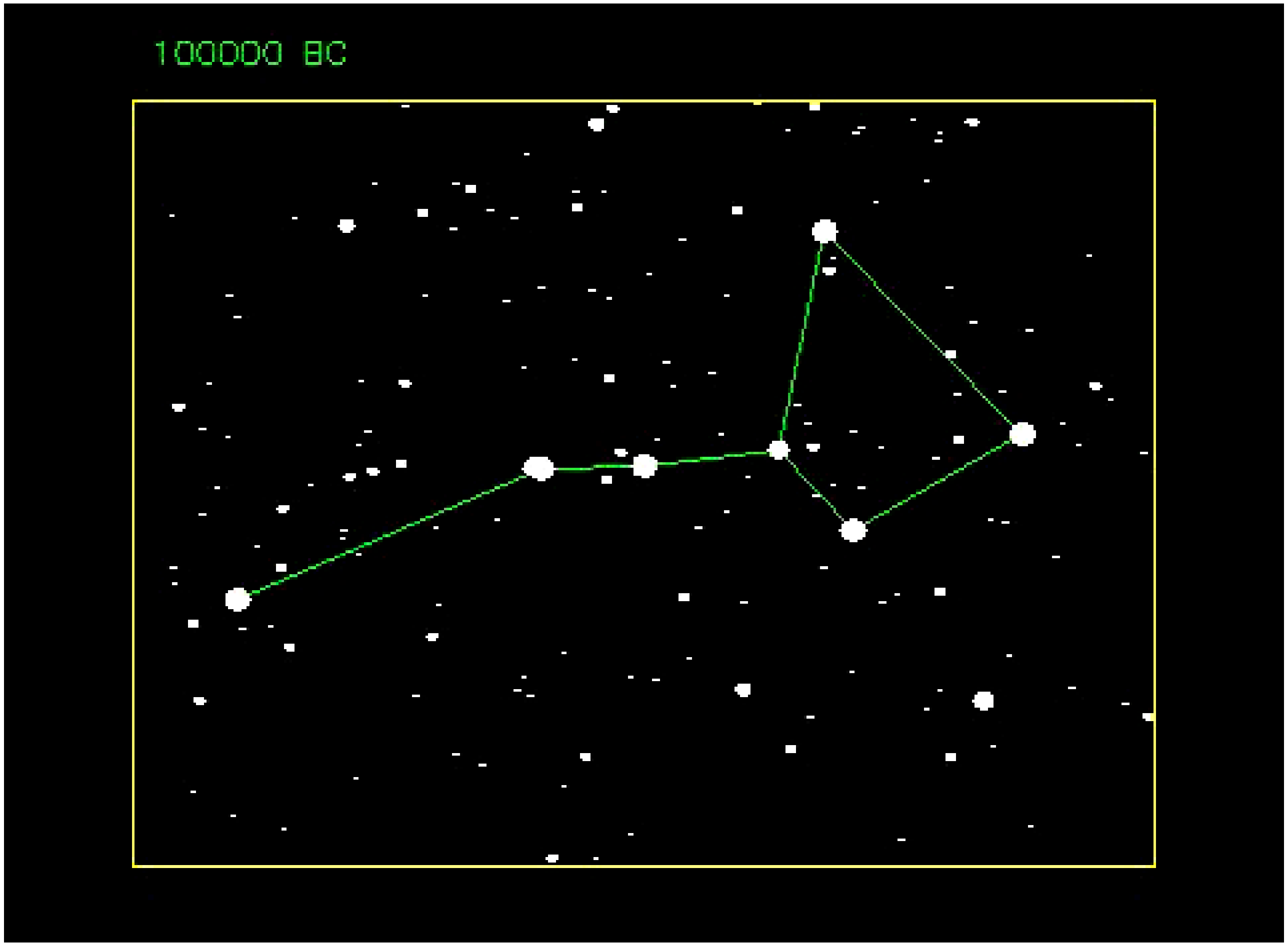
In practice, observing parallaxes is very difficult, because the angles involved are not only very small, but also the earth's atmosphere blurs our images and prevents accurate observations. Even the very closest star moves (I.e. has a parallax angle of) only about 1/200 the size of the moon.

Satellites, on the other hand, can do a much better job, because they are above the problematic atmosphere. In 1989, ESA launched the Hipparcos satellite which has now measured the parallaxes (and therefore the distances) to over 120,000 stars.

In addition to the *apparent* motions of parallax, stars have *true* motions because they are all moving around the Milky Way. These motions are called proper motions and are typically less than 1 arcsecond per year. The appearance of the sky is therefore gradually changing over the millenia.

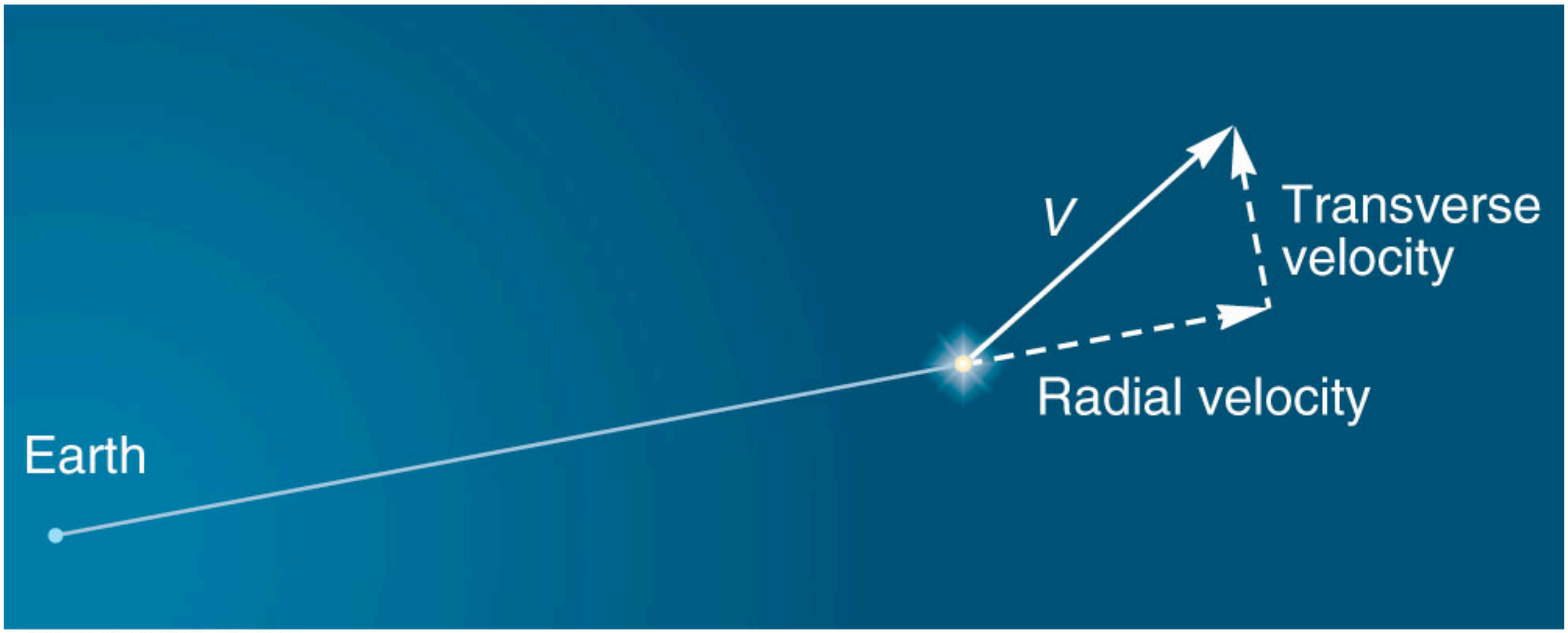


Remember, the stars in most constellations are not physically associated with each other, so as each star drifts differently (and with a different proper motion speed) the constellations will change.

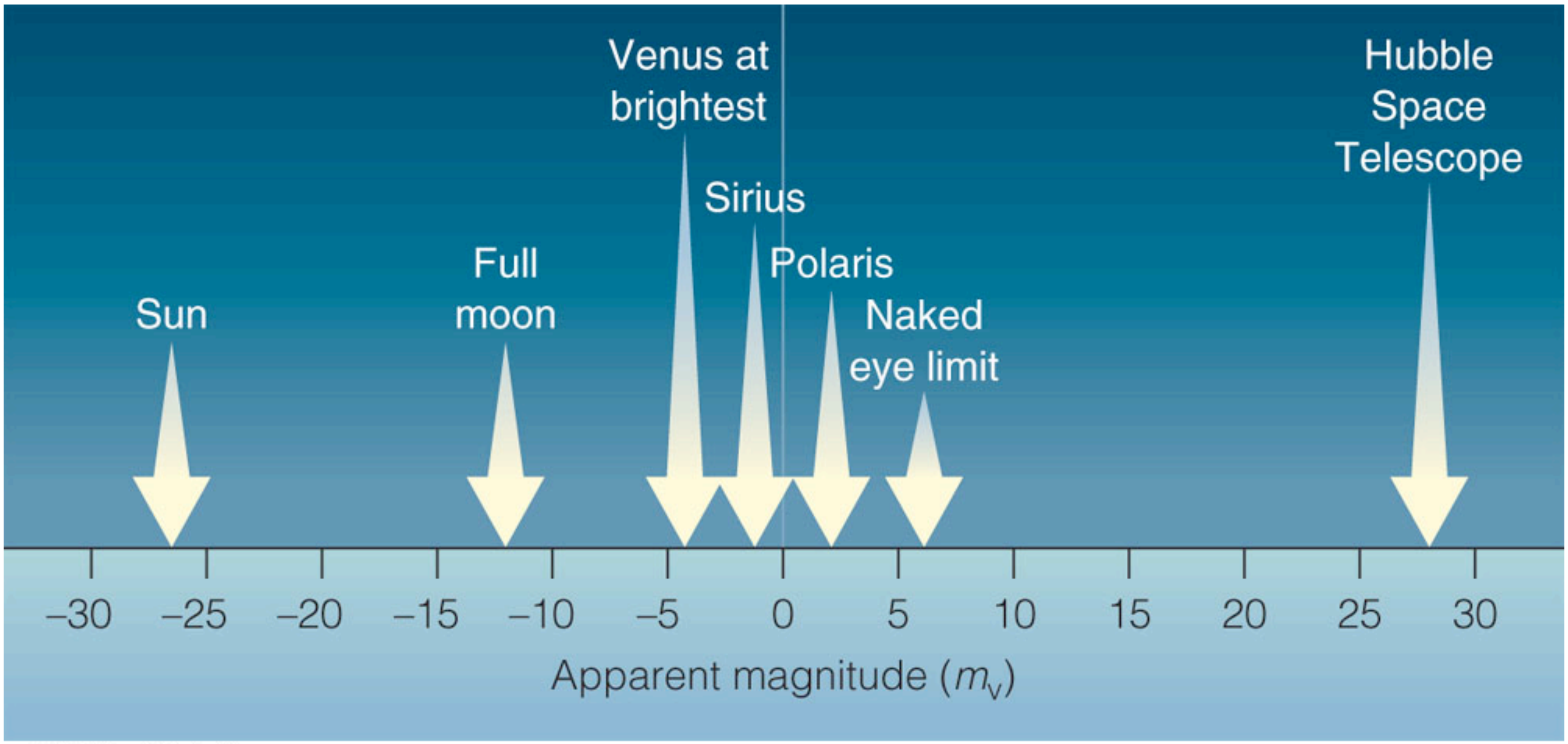


In this movie, we see the appearance of Ursa Major (the Big Dipper) evolving over a period of 200,000 years. Why do some stars have higher proper motions than others?

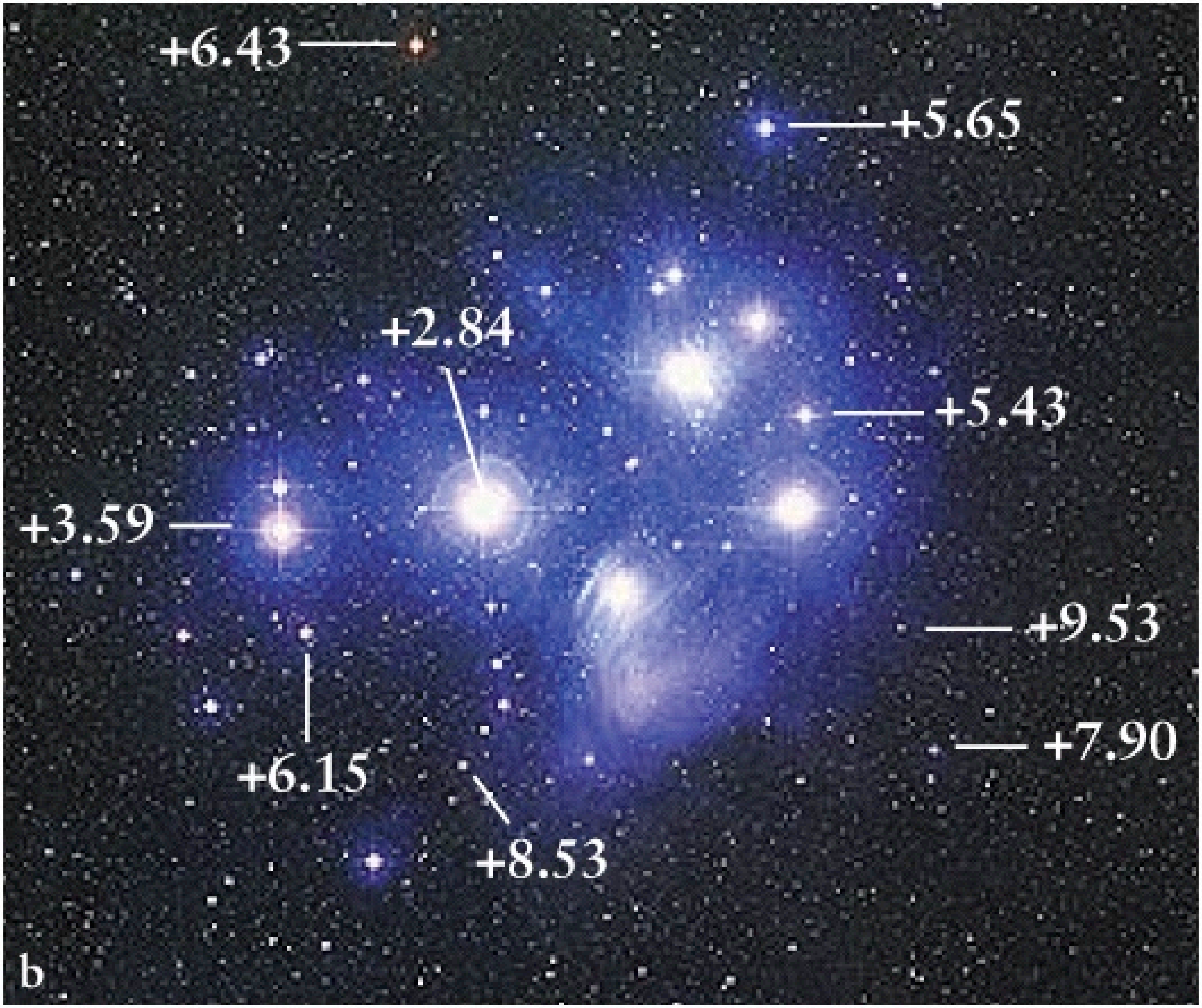
The proper motion of the stars is the same as the transverse motion. If we want to know the true motion of a star through space we need to combine its transverse velocity (as measured from a proper motion) with its radial velocity (as measured from a Doppler shift).

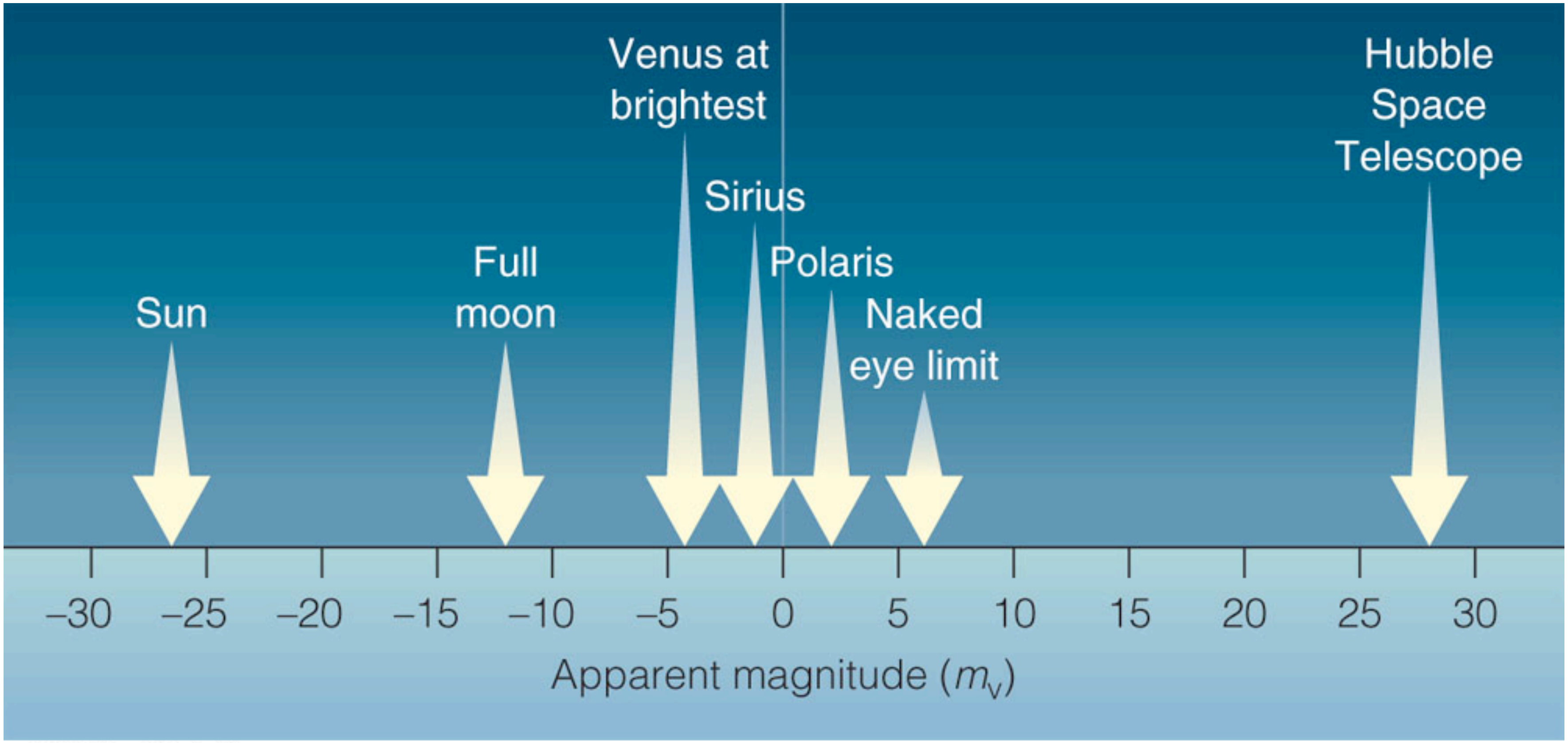


Having pinned down stellar distances, we are now going to think about their brightnesses. Invented by the Greek astronomer, Hipparchus, the scale of “apparent magnitudes” is a bit quirky! First, the brighter an object, smaller its apparent magnitude. Extremely bright objects even have negative magnitudes.



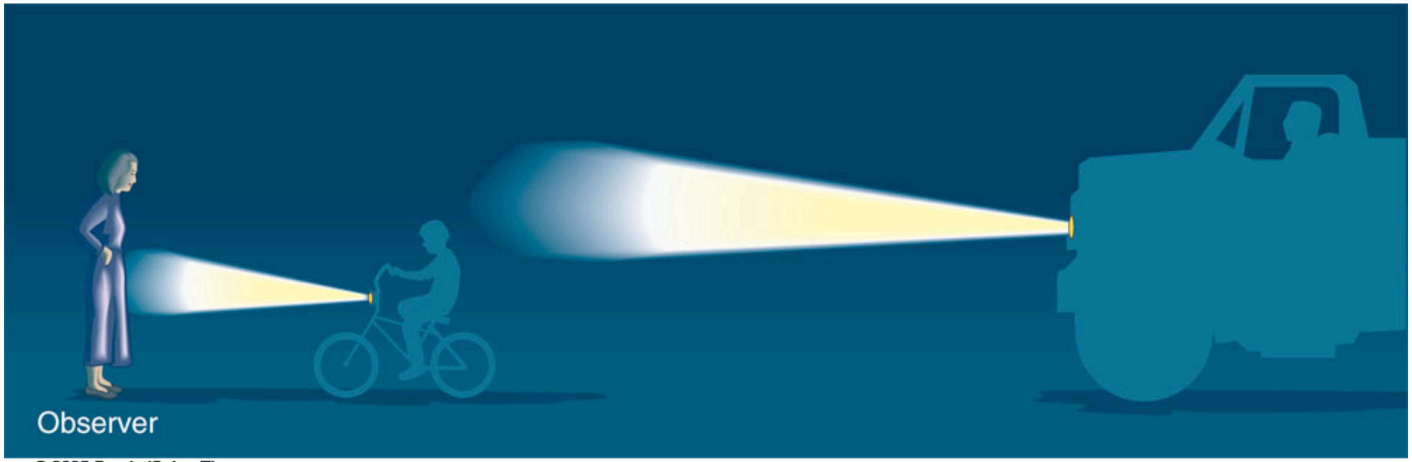
Which of these stars is brightest?





The faintest stars we can see with the naked eye are about 6th magnitude. Powerful telescopes like the Hubble can see down to about 27th magnitude. Show that this is 200 million times fainter than the naked eye limit.

However, apparent magnitudes need to be combined with distances. Without knowing the distance, we don't know whether a given star is bright, but distant, or faint, but nearby.



Recall that astronomers measure the brightnesses of stars using the magnitude scale, such that brighter stars have smaller magnitudes. The magnitude that we measure is called the apparent magnitude (m) of the star. The apparent magnitude contains information on both how bright the star really is, but also how close it is.

We therefore define the absolute magnitude (M): the apparent magnitude a star would have it were 10 pc away

In this way, all stars can be put on an equal footing. The actual equation for absolute magnitude is

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

In order to make life simple (and avoid using the nasty formula!) we can make a table of m-M, which is also known as the distance modulus, and d (see Table 9.1 in Seeds). This table is then an easy way to calculate the distance to a given star given the difference between the apparent and absolute magnitudes.

Example 1: What is the distance modulus for a star that is 100 pc away?

Answer: Distance modulus is just m-M, which we read off the table: 5 magnitudes.

Example 2: If a star has an apparent magnitude of 4.3 and is 40 pc away, what is its absolute magnitude (M)?

TABLE 9-1
Distance Moduli

$m_V - M_V$	d (pc)
0	10
1	16
2	25
3	40
4	63
5	100
6	160
7	250
8	400
9	630
10	1000
⋮	⋮
15	10,000
⋮	⋮
20	100,000
⋮	⋮

Answer: from the table we see that for a star 40 pc away, m-M = 3. If the apparent magnitude (m) is 4.3 then the absolute magnitude, M=m-3 = 4.3 - 3 = 1.3.

Example 3: Which star is intrinsically brighter, A or B?

	Star A	Star B
Apparent magnitude (m)	3.3	2.1
Distance (pc)	63	16

TABLE 9-1
Distance Moduli

$m_v - M_v$	d(pc)
0	10
1	16
2	25
3	40
4	63
5	100
6	160
7	250
8	400
9	630
10	1000
⋮	⋮
15	10,000
⋮	⋮
20	100,000
⋮	⋮

Answer: Calculate the absolute magnitude for both stars using the table of distance moduli.

Star A: For d=63 pc, m-M=4. Therefore M=m-4 = -0.7

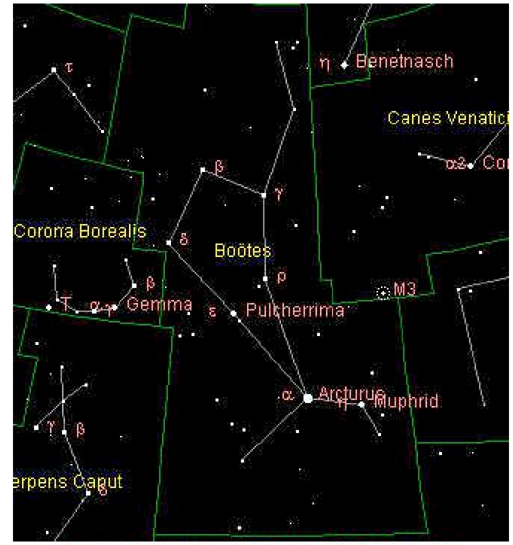
Star B: For d=16pc, m-M=1. Therefore M=m-1=1.1

Star A has a smaller absolute magnitude (-0.7 is less than 1.1) so it is intrinsically brighter, even though its apparent magnitude is fainter.

Although we have been talking about apparent and absolute magnitudes, strictly these are visual magnitudes, because they only account for the light at visible wavelenths. We can also define the bolometric magnitude (both apparent and absolute) which takes into account light at other wavelengths. The bolometric magnitude is therefore a measure of total light, or total luminosity. Again, we can define apparent and absolute bolometric magnitudes.

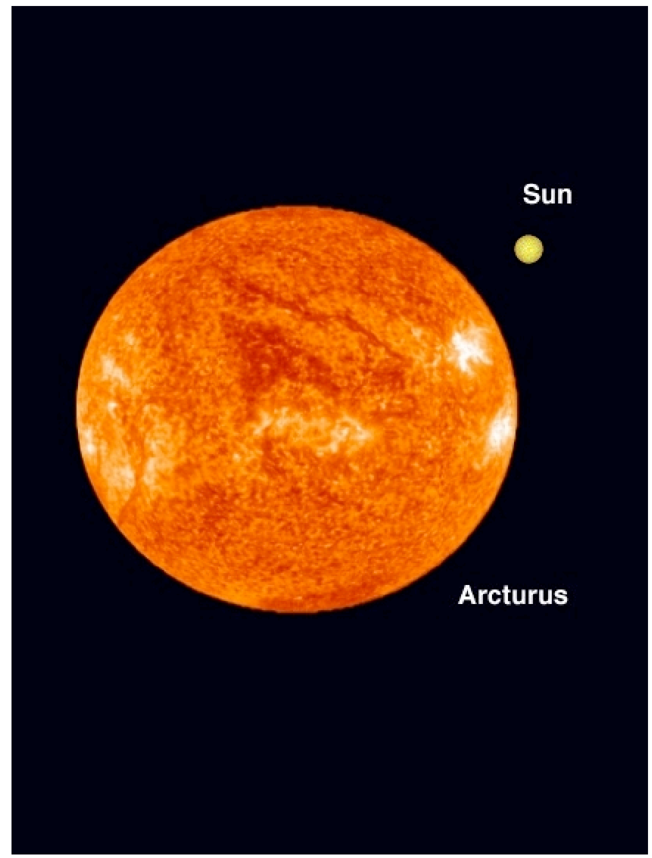
The absolute bolometric magnitude of a star is the magnitude it would have if it were placed at a distance of 10 pc and we could see at all wavelengths.

Example: The star Arcturus has an absolute bolometric magnitude of -0.3. How many times as more luminous is Arcturus than the sun (whose absolute bolometric magnitude is 4.7)?



Arcturus (Alpha Bootis), RA 14 15 39.7 Dec +19 10 57

Answer: The sun's bolometric magnitude is 5 magnitudes fainter than Arcturus. Each magnitude is a factor of 2.5 in brightness, so 5 magnitudes gives 2.5x2.5x2.5x2.5x2.5 = 100 (see also Table 2.1 in Seeds). 100 times brighter means 100 times more luminous, so Arcturus is 100 times more luminous than the sun.



In the previous example, we saw that Arcturus is much larger (as well as being much more luminous) than the sun. This is because a larger surface area can radiate more photons. Another factor that affects luminosity is temperature. Taken together, we have the following formula:

$$L/L_{sun} = (R/R_{sun})^2 \times (T/T_{sun})^4$$

We don't actually have to divide the radius and temperature by the solar values, because the subscript "sun" just means we'll put the values in in units the sun's luminosity, radius and temperature.

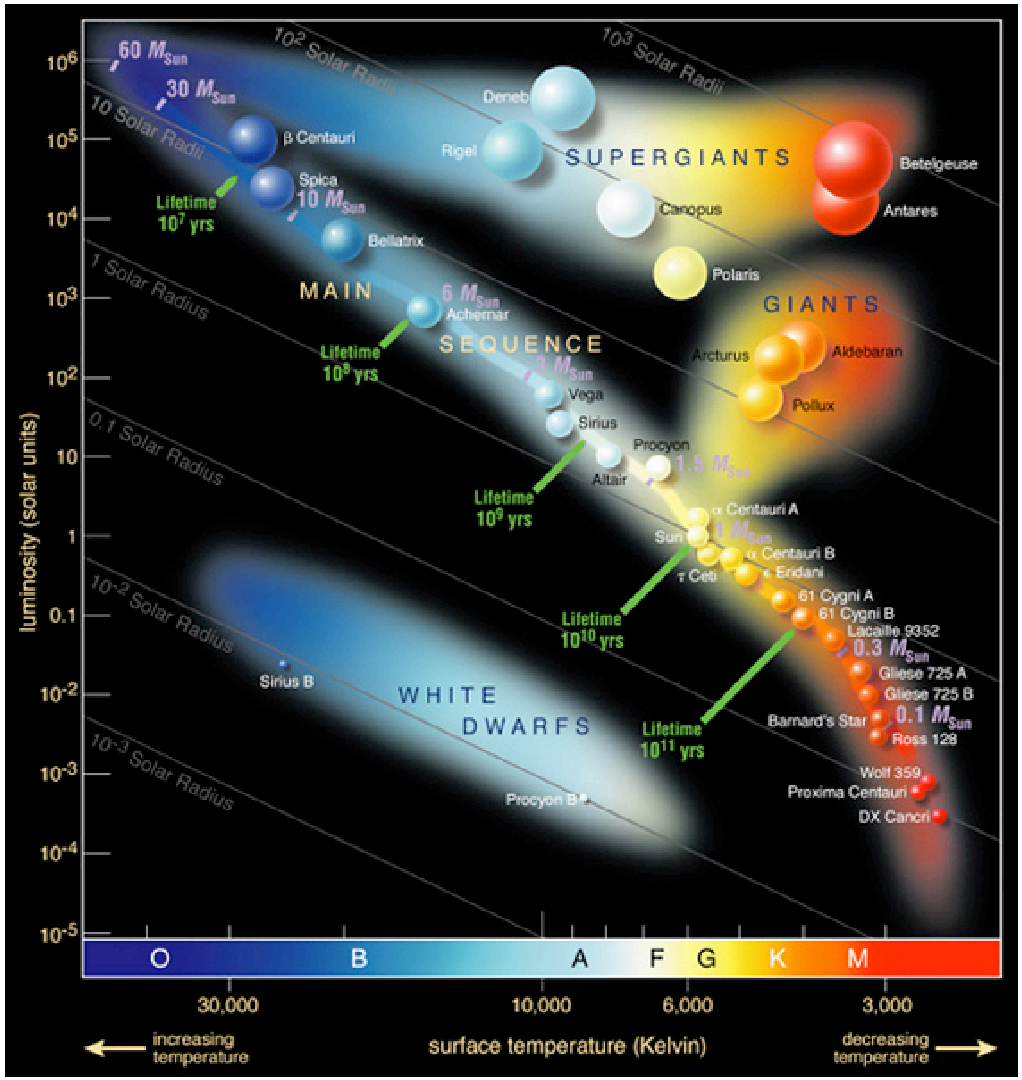
Example 1: A star has the same temperature as the sun, but twice the radius, what is its luminosity?

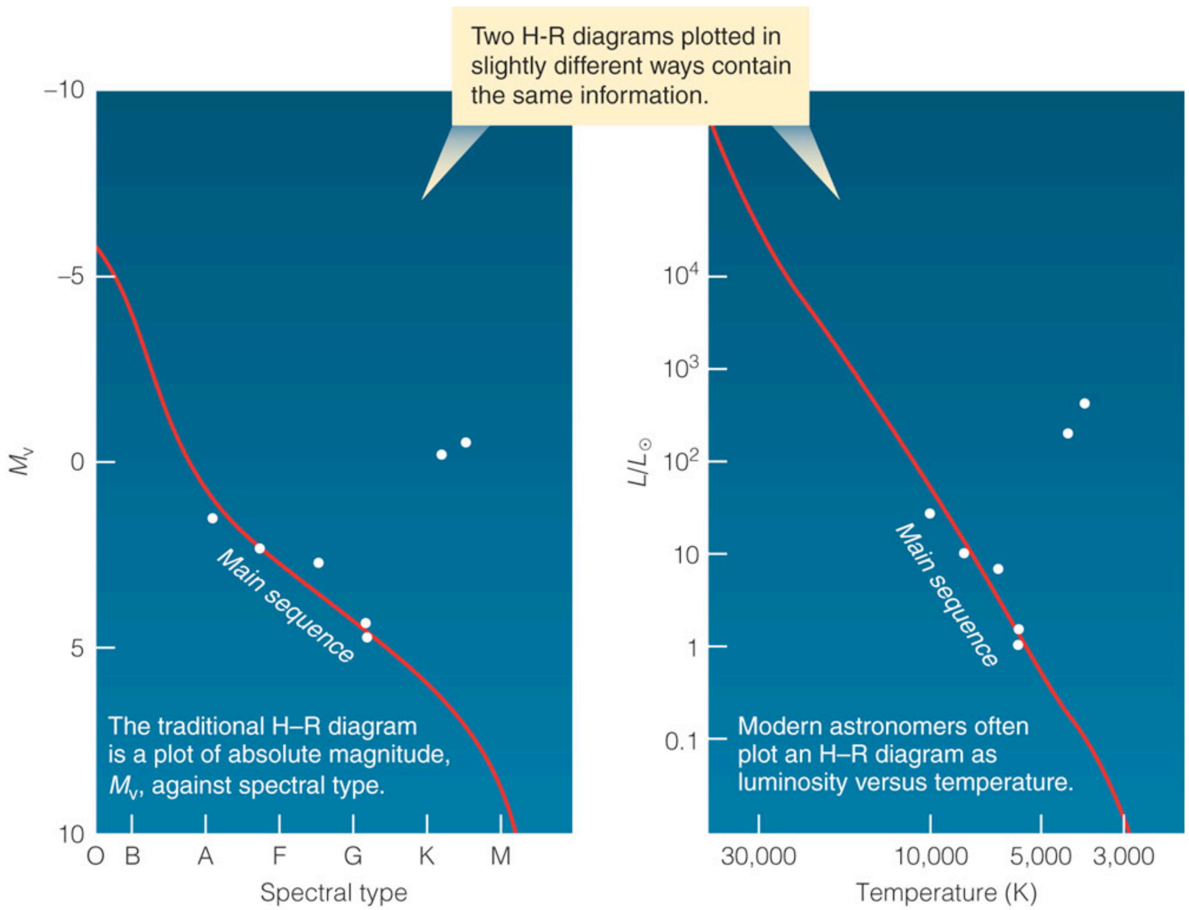
Answer: $L/L_{sun} = (R/R_{sun})^2 \times (T/T_{sun})^4$
The temperature of the star is the same us the sun, so
$(T/T_{sun})^4 = 1$ and $(R/R_{sun})^2 = 2^2 = 4$.
So $L = 1 \times 4 = 4\ L_{sun}$

Example 2: A star has half the sun's temperature, but four times the radius, what is its luminosity?

Answer: $L/L_{sun} = (R/R_{sun})^2 \times (T/T_{sun})^4$
$(T/T_{sun})^4 = 0.5^4 = 0.0625$ and $(R/R_{sun})^2 = 4^2 = 16$.
So $L = 0.0625 \times 16 = 1\ L_{sun}$

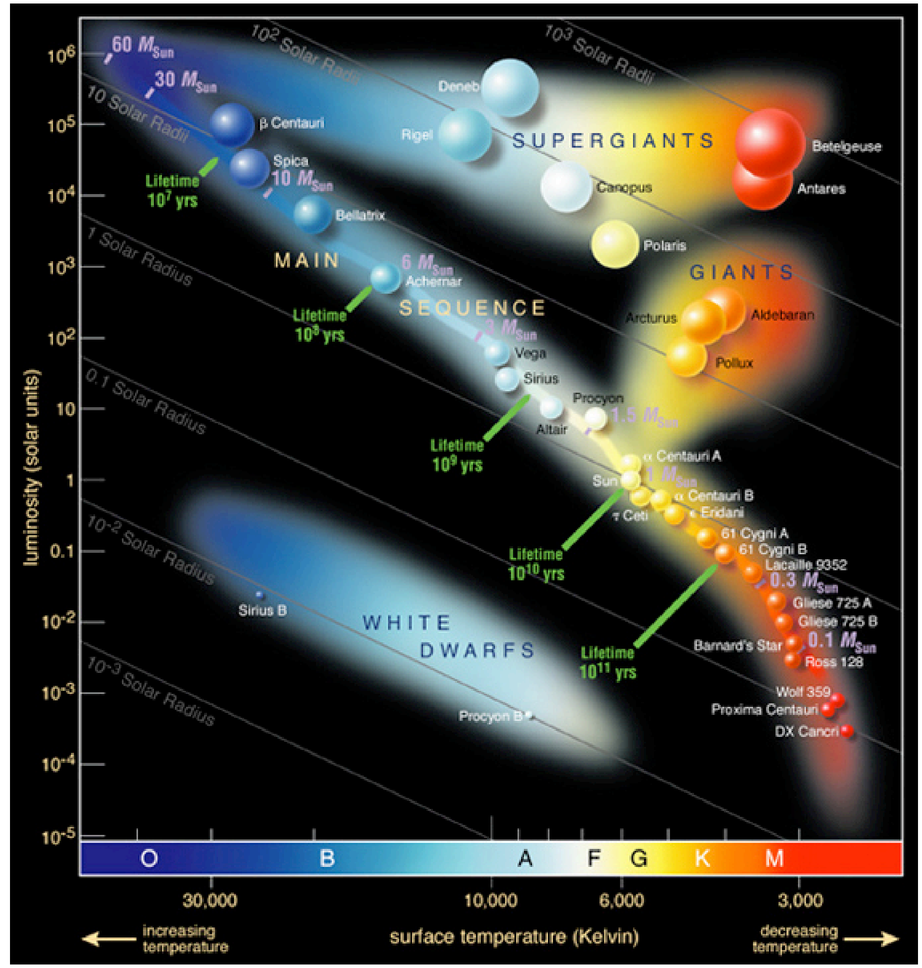
Knowing the temperature and luminosity of a star therefore also tells us about its size. In order to sort stars by L and T, astronomers draw a Hertzsprung-Russell (HR) diagram.





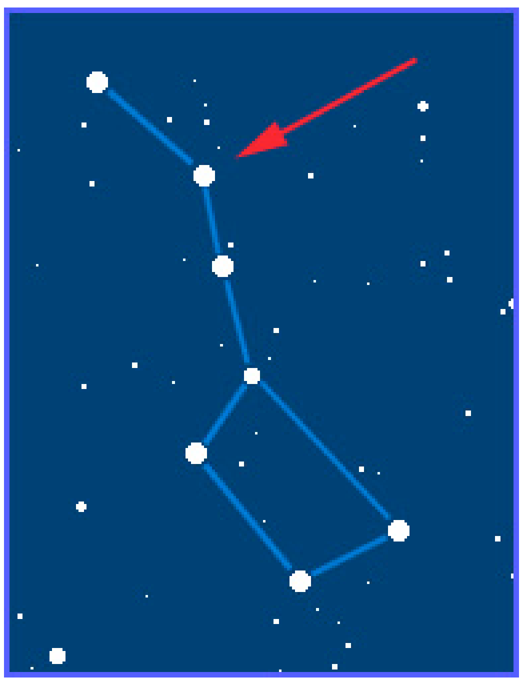
The HR diagram is a plot of L and T (or we could plot the magnitude instead of L). Since a star's spectral type is governed by its temperature, we can also write the spectral type along the temperature axis.

Stars are not scattered randomly on the HR diagram. Most (~90%) are found on a diagonal strip called the main sequence. Note that stars with high temperatures tend to have high luminosities. These stars are also physically larger than lower luminosity stars. Remember, for a given temperature, a larger radius gives us a higher luminosity. For this reason, the supergiant stars are much more luminous



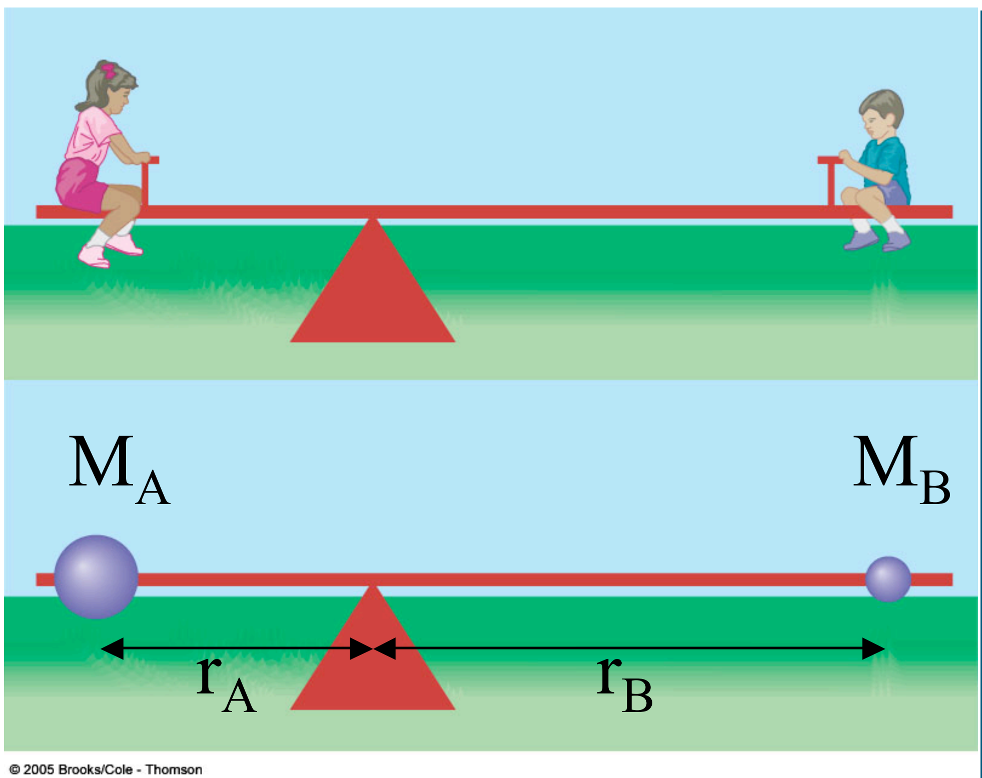
than main sequence stars of the same temperature. Temperatures also govern the star’s colour: cooler stars appear redder and hotter stars appear bluer.

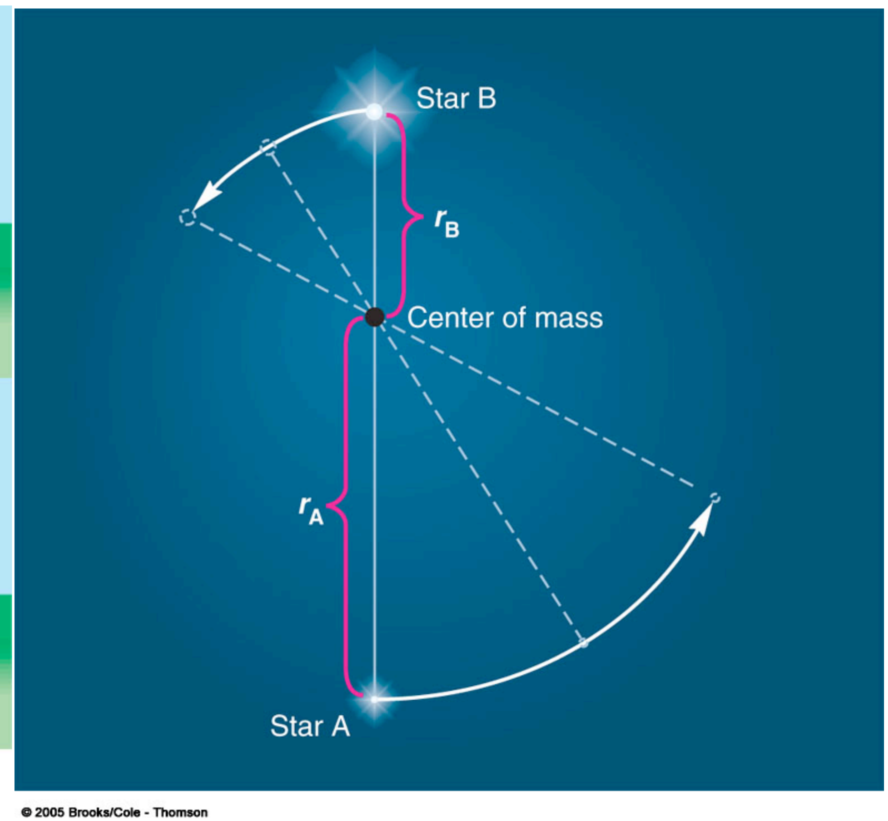
Unlike temperature or luminosity, the mass of a star is not something we can measure just by observing its magnitude or colour. In order to measure the mass of a star, we need to find binary stars. These are surprisingly common, in fact somewhere between 60-80% of stars are in multiple systems. In this sense, the sun is unusual.



Mizar is a double star in the Big Dipper

In order to measure the mass of a star, we study the way it moves. This is easiest in a binary system where we can watch both stars orbiting around a common centre of mass. Remember, the centre of mass will be closer to the higher mass object, like on a seesaw.

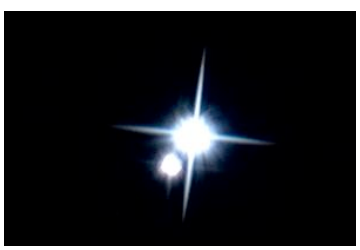




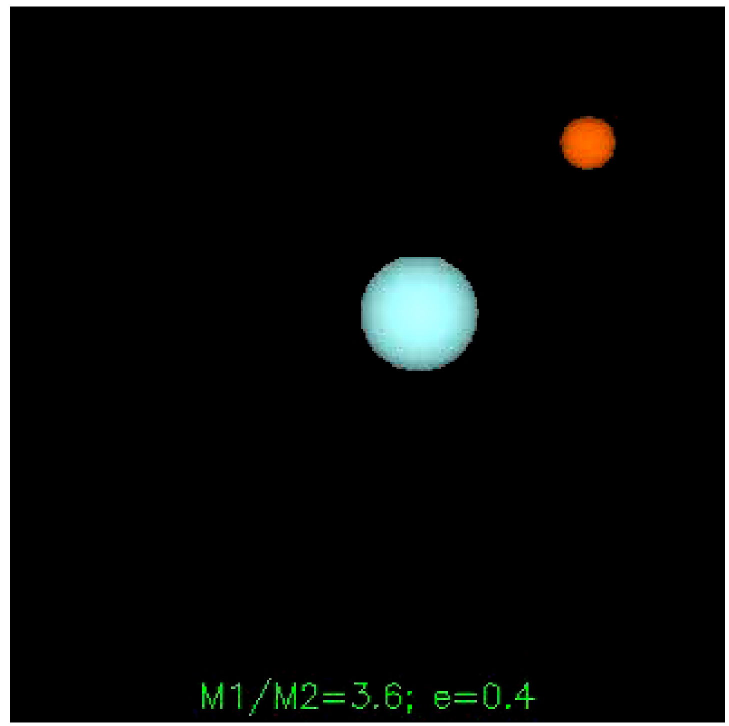
There are many different types of binary star. The most obvious is the visual binary which can be detected with the naked eye or a telescope. We've already seen one example of a visual binary: Mizar in the Big Dipper which can easily be discerned with binoculars. Here are some others:

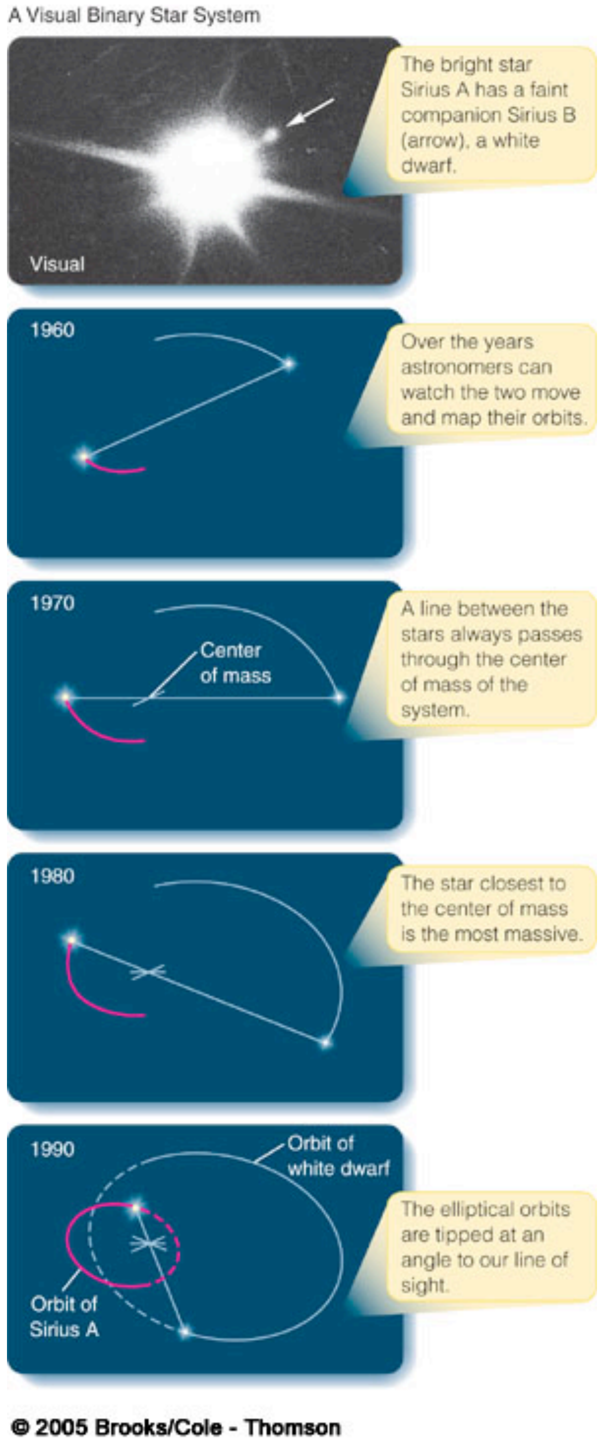
Albireo

Epsilon Lyrae



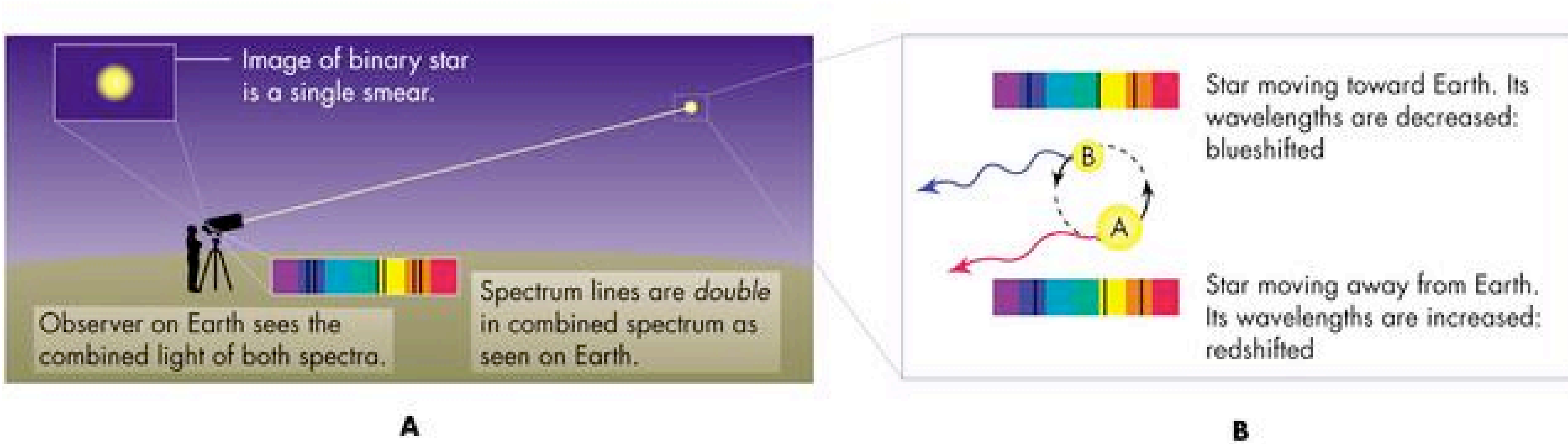
Cor caroli





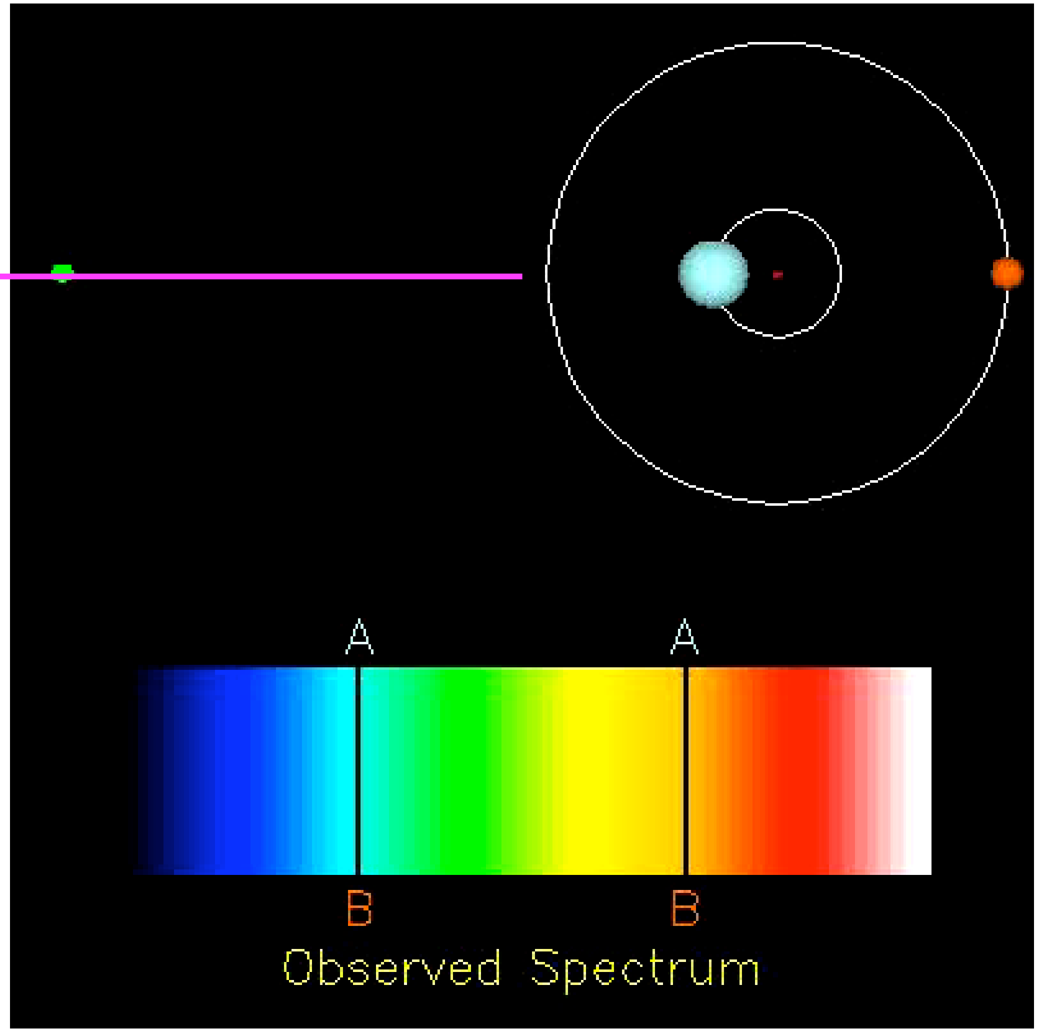
Visual binaries can be studied similar to our worked example of the 3 and 1 solar mass binary. However, some visual binaries have quite long periods. For example, Sirius A and B (the latter of which is a faint white dwarf star) has a period of 50 years. Binaries with periods much longer than this become impractical to study. Also, many binaries are just too close to separate with our telescopes, so we need alternative ways to study them.

Close binaries appear as a single point of light and do not appear as visual binaries. However, a spectrum of the combined stellar image often reveals the binary's nature.

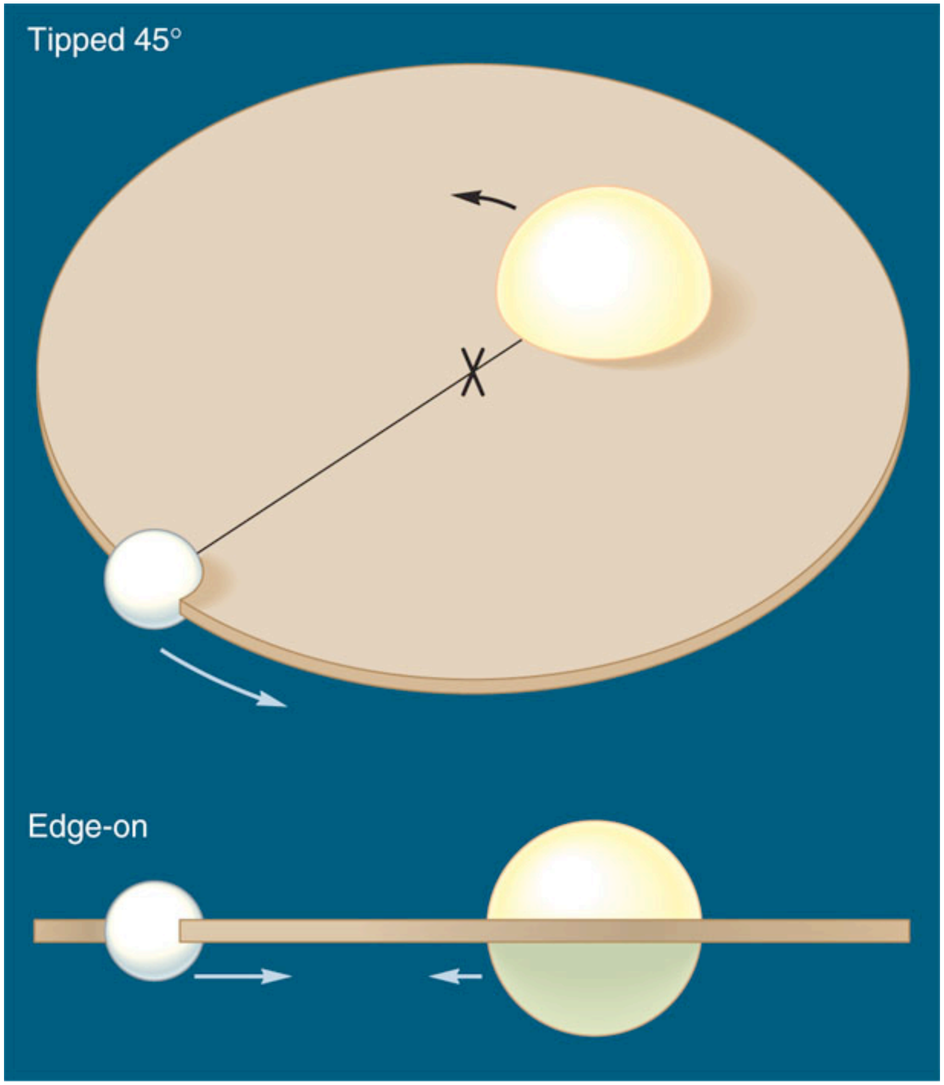


The spectrum is a combination of light from both stars, so will show absorption lines from both stellar atmospheres. These lines will appear to shift in opposite directions - a clear sign that there must be more than one object. This is called a spectroscopic binary.

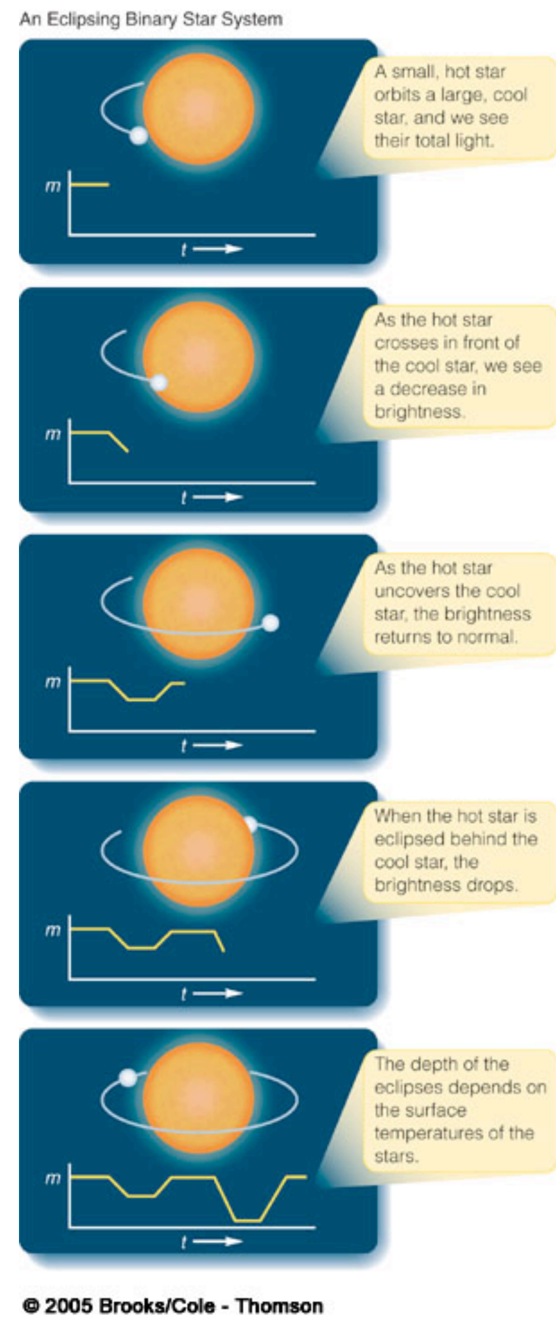
Spectroscopic binaries can only be seen most easily when their orbits are almost edge on, so that we see large radial velocities causing a Doppler shift



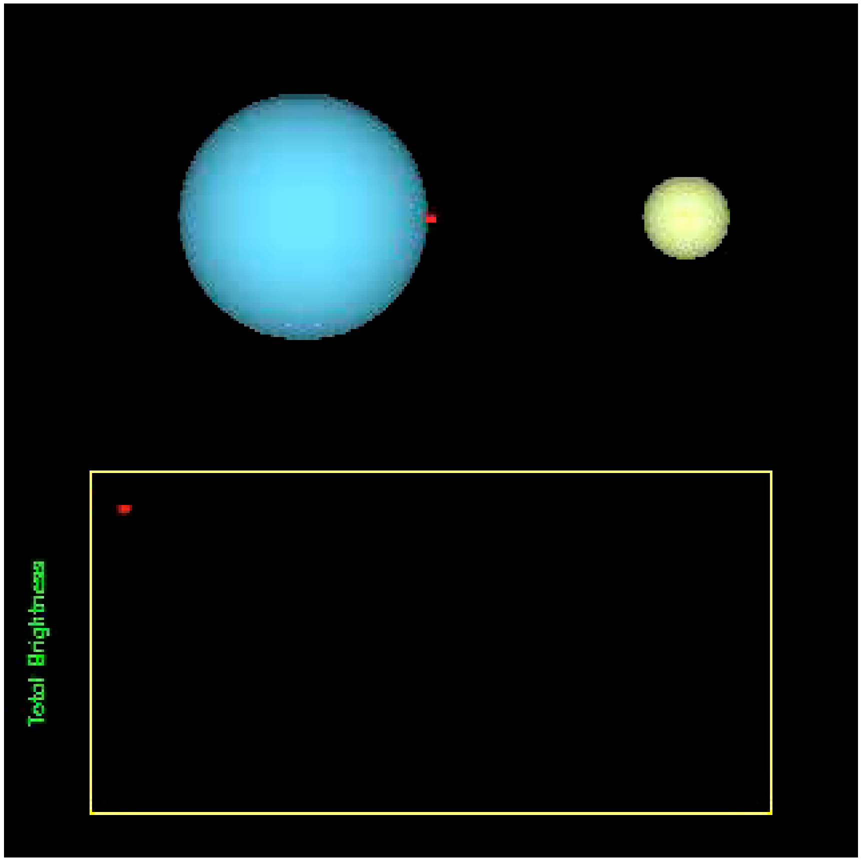
If tipped at an angle of 45 degrees we could still detect a spectroscopic binary, because the stars still seem to have a component of their velocity that is radial (ie moving directly away or towards us). If binary orbits are very well aligned (ie almost perfectly edge-on) we observe eclipsing binaries.

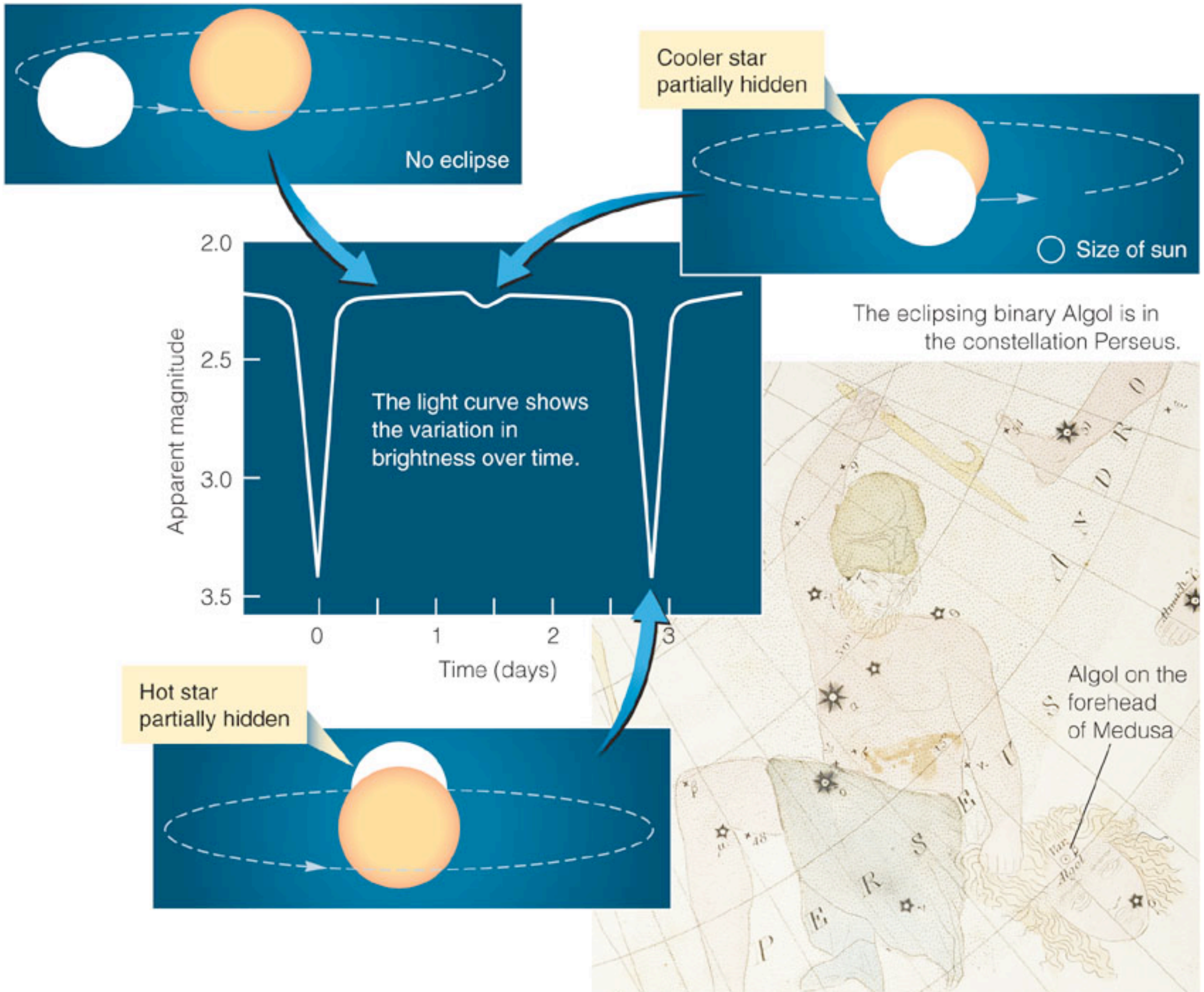


Eclipsing binaries are studied by watching how the total brightness (magnitude) of the binary changes as a function of time. The magnitude will dip twice during an orbit, once as the fainter star goes behind the brighter one, and once as it goes in front. The binary is fainter when the faint (cool) star is superimposed on the brighter (hotter) star because a 'patch' of the bright star is replaced by an area of fainter flux (ie the surface of the cooler star). The shape of the dips also tells us about the relative sizes of the 2 stars.



In this movie, we see these 2 dips in brightness, but also notice how the positions of the stars wobble as they also move around their centres of mass (shown by the pink dot).





If the orbit is not perfectly edge-on, we might only see partial eclipses, which lead to less well defined dips. Algol is a well-known, naked eye eclipsing binary.

Review:

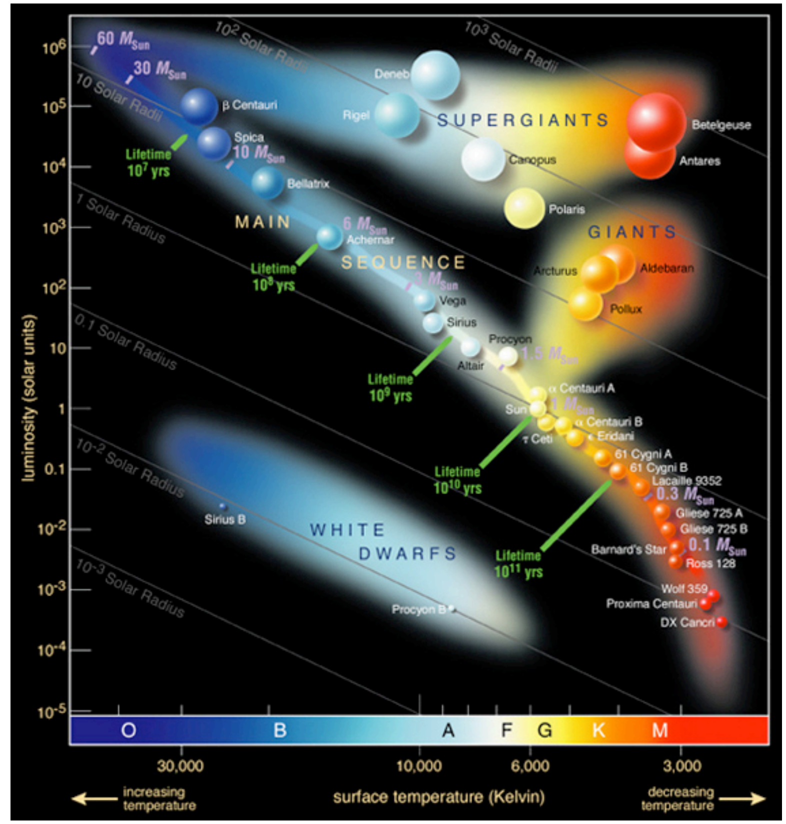
- We can measure the distances to stars by parallax
- Once we know the distance, we can work out the absolute magnitude using the tabulated distance modulus
- We can compare the absolute bolometric magnitude of any star with the sun and hence determine its luminosity, L
- We know a star's temperature from its spectral type, combing T with L we know the star's size from

$$L/L_{sun} = (R/R_{sun})^2 \times (T/T_{sun})^4$$

- We can determine the mass of a star if it is in a binary system

We've gone a long way towards answering the questions we set out at the beginning of this chapter

Beyond the properties of individual stars, the HR diagram tells us a lot about the life cycles of stars. We will see in the following chapters that the tight relationship in mass and luminosity (the main sequence) tells us about the interiors of stars. A survey of stars near the sun will not give us a fair picture of stars in the galaxy. Also, if we just take the brightest stars, such as those visible to the naked eye, we will be biased towards those that are intrinsically more luminous (ie bright absolute magnitude).



The nearest star to the Sun is Proxima Centauri, about 4 light years away.

Even though it is close, it is quite faint (the red star in the middle of this picture) and not visible to the naked eye. Proxima Cen is part of a triple star system called Alpha Centauri.

The brightest member of the triplet is the third brightest star in the sky and is much like our sun.

In order to take an honest census of stars, we need to cover a large volume and include lots of stars, in order to make sure we don't miss the faint ones or the rare ones. A fair census such as this reveals that most stars are on the main sequence and that most stars are on the main sequence and that lower mass, cooler stars are more common than high mass, hot ones.