The lives of stars

- Now that we have seen how we can find out various properties of stars – mass, luminosity, distance, radius – we can start to talk about their lives.
- The lives of stars are extremely long – millions, billions or even trillions of years. So how can we understand them at all, when the whole of recorded human history is less than 1% of the life of even the shortest-lived star?
- Luckily, we have a huge sample to work with. There are 200 billion stars in our galaxy alone. With such a large number, all born at different times, all with different masses, we see stars at all stages of their lives.

The lives of stars

- The most massive stars have the shortest lives. They are also the brightest. This makes it quite easy to work out where star formation is happening, or has recently happened – if you see hot, young bright stars, then they must have formed quite recently.
- A great example is the Pleiades – currently very clearly visible, high in the night sky at about 9pm.

The lives of stars

The lives of stars

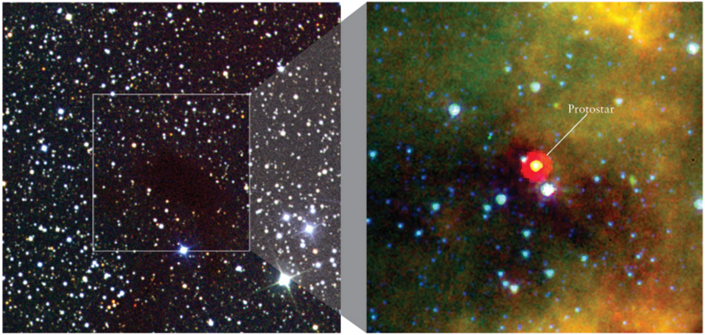
- What you find is that often, where you find hot, blue and therefore massive and young stars, you also find lots and lots of hydrogen gas – like in the Orion Nebula:

The lives of stars

- These regions of hydrogen gas, in which stars are forming, are called **H II regions**. The name comes about because hydrogen gas can be either neutral (H I), or ionised (H II), and these regions are ionised, by the light from the stars forming within them.
- Looking more closely, we see that within the bright H II regions are dense, dark, cold, dusty clumps. These are called Bok globules.

The lives of stars

- Dust absorbs absorbs more blue light than red light, so by observing the galaxy in red light you can see further through the dust clouds. You can see even further by observing infrared light.
- When we look at the dense dark clouds within H II regions in infrared light, we see that they have stars within them.



(a) A dark nebula

(b) A hidden protostar within the dark nebula

Star formation

- Typically, hundreds or thousands of stars form in one go. The result is star clusters like the Pleiades.
- The hot luminous massive members of the cluster "blow away" the cloud of dust and gas from which they formed, and the cluster become visible at optical wavelengths.

Stellar lifetimes

- Stars stay on the main sequence until they run out of hydrogen in their cores. The time this takes depends on the mass – more massive stars burn their fuel much more quickly.
- Stellar lifetimes range from a few million years for very massive stars to hundreds of billions of years for the lightest.

The deaths of stars

- Stars on the main sequence are in *hydrostatic equilibrium* - the energy generated by nuclear fusion stops the star collapsing under gravity.
- When the fuel runs out, the balance between gravity pulling material in and gas pressure pushing it out breaks down. The core begins to contract because energy is no longer being produced.
- As the core contracts, it gets hotter and hotter, as the pressure increases. What happens next depends on the mass of the star.

Low-mass stars

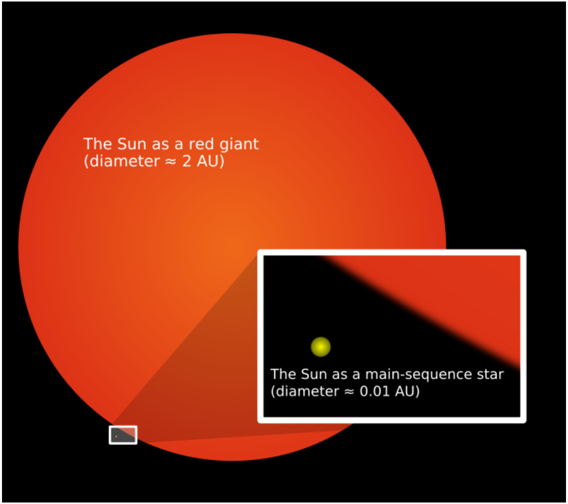
- For stars with less than 0.4 $M_{\odot}$, the temperature does not get hot enough for anything else to happen. The star will end its life as an inert ball of helium, just radiating away its internal heat.
- But the universe is not yet old enough for any stars this light to have burned all their hydrogen.

Medium-mass stars

- For stars heavier than $0.4\,M_\odot$ and lighter than 2 or 3 $M_\odot$, the core contraction and heating makes the outer layers expand and cool greatly. The star becomes cooler but much larger, and thus more luminous. It is a *red giant*.
- The core will eventually heat up to a temperature of 100 million K. Just as hydrogen nuclei can fuse to form helium, releasing some energy, so helium nuclei can fuse to form carbon and oxygen, releasing some energy.
- The temperature and density need to be much higher, and less energy is released per atom.

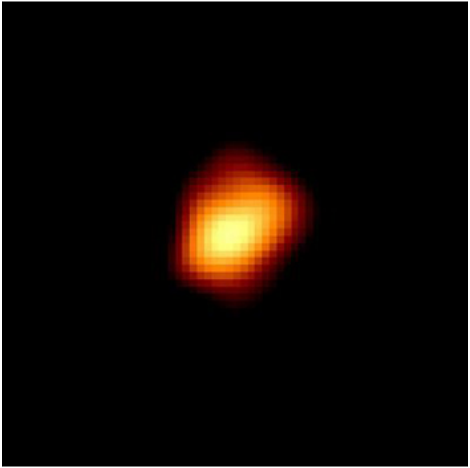
The deaths of stars

- Red giants are extremely large!

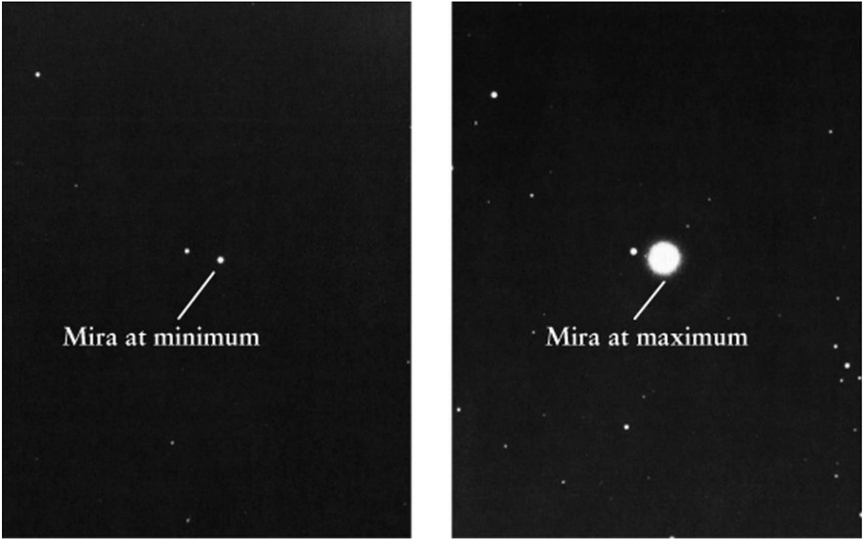


The deaths of stars - Mira

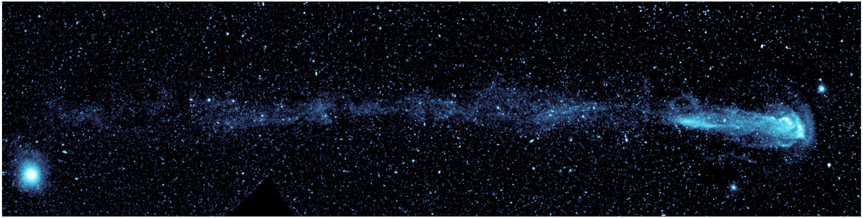
- Evolved stars almost always go through phases where they are pulsating, and varying in brightness. A great example is Mira.



The deaths of stars - Mira

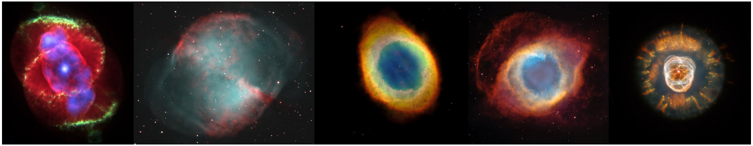


The deaths of stars - Mira



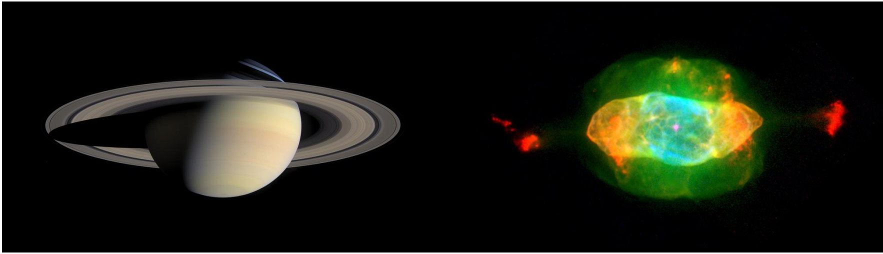
The deaths of stars - planetary nebulae

- Instabilities and pulsations drive away the outer layers from stars. Red Giants can lose $10^{-7}\,M_\odot$/year. (The Sun loses about $10^{-14}\,M_\odot$/year)
- If the mass of the star is lower than about 8 solar masses, this mass loss eventually puts an end to its evolution. The reduced pressure stops the nuclear reactions. The atmosphere drifts away, and is lit up by the exposed core. A *planetary nebula* has formed.



The deaths of stars - planetary nebulae

- Named for supposed resemblance to planets



The deaths of stars - massive stars

- Stars with masses greater than $\sim 8\,M_\odot$ are heavy enough that nuclear reactions can still proceed in the core despite mass loss.
- The core will eventually get hot enough for carbon to undergo fusion, forming oxygen, neon, sodium and magnesium.
- The star will go on to fuse neon, then oxygen, then silicon.

The deaths of stars - massive stars

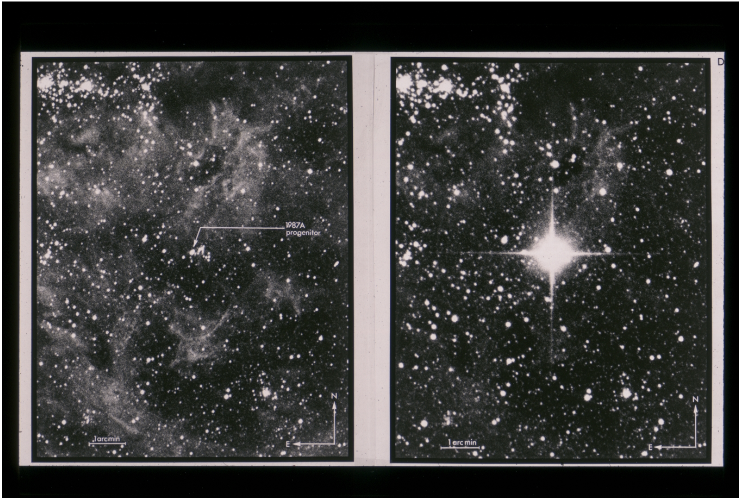
- Each step proceeds more and more quickly:
  - Hydrogen-burning – a few million years
  - Helium burning – a few hundred thousand years
  - Carbon fusion – a few hundred years
  - Neon fusion – a year
  - Oxygen fusion – a few months
  - Silicon fusion – over and done with within a day.
- What next?

The deaths of stars - massive stars

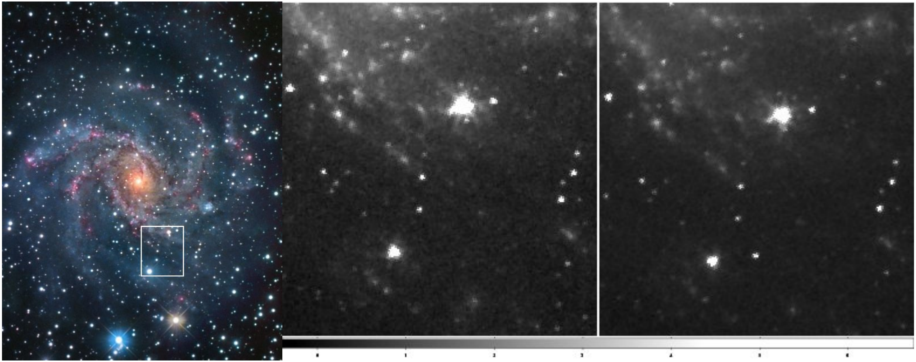
- The most stable nucleus is iron. Once silicon has fused to form iron, the star has nowhere to go. The core’s energy source runs out suddenly.

The deaths of stars - supernovae

- The core collapses. The outer layers are suddenly unsupported, and fall in. They crash into the core, and a huge shock wave rebounds outward, destroying the star in a supernova.



The deaths of stars - supernovae

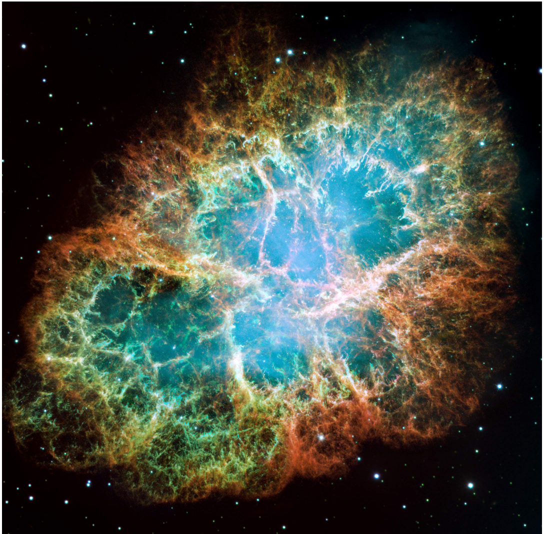


The deaths of stars - supernovae

- Supernovae briefly shine as brightly as a galaxy – and emit as much energy as *hundreds* of galaxies!!
- What is left behind? A supernova remnant – the slowly fading outer layers of the star, moving away into space.
- And at the centre – something exotic.

The deaths of stars - supernovae

- Most famous supernova remnant is the Crab Nebula – the result of an explosion seen by Chinese astronomers in 1054.



The deaths of stars - supernovae

- For a relatively low-mass supernova, the remaining object at the centre might be a white dwarf. Mostly, though, the mass of the remaining core is enough that protons and neutrons are compressed together into neutrons, and you get a neutron star.
- A neutron star might be as massive as the Sun but only a few miles across.

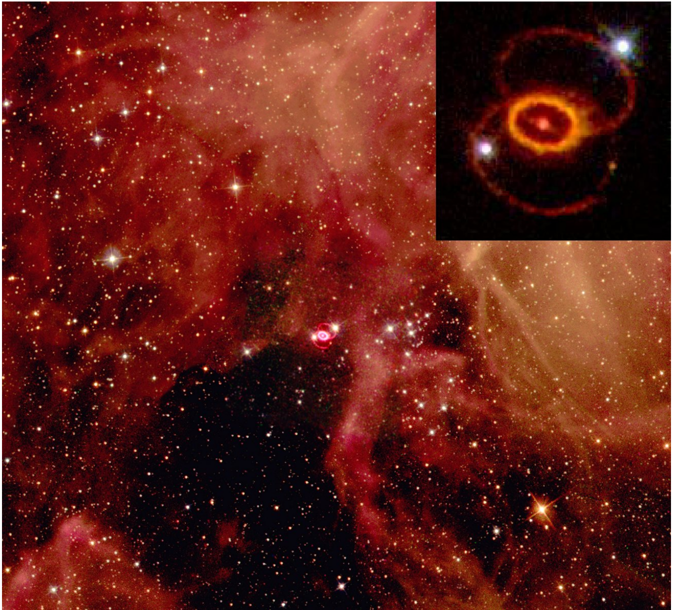
The deaths of stars - black holes

- When a really massive star explodes, its remnant may be too heavy to form a neutron star.
- It could form a black hole - an object with such strong gravity that not even light can escape.
- Suspected black holes are detected because material spiralling into them gets incredibly hot, and emits X-rays

Cosmic recycling

- The universe, in the beginning, was more or less just hydrogen and helium. Everything heavier – like the molecules we are made of – was formed in the cores of stars.
- The death of a star can trigger the birth of other stars. The shock wave from a supernova can impact on nearby clouds of interstellar gas, causing them to start collapsing and eventually giving birth to a new cluster of stars.

Cosmic recycling



Cosmic recycling

- The new stars will incorporate some of the material from the stars before them that exploded. In this way, the amount of elements heavier than hydrogen and helium in stars is increasing as the universe gets older.
- NB: astronomers refer to anything that is not hydrogen or helium as a metal!

The Milky Way

The Milky Way

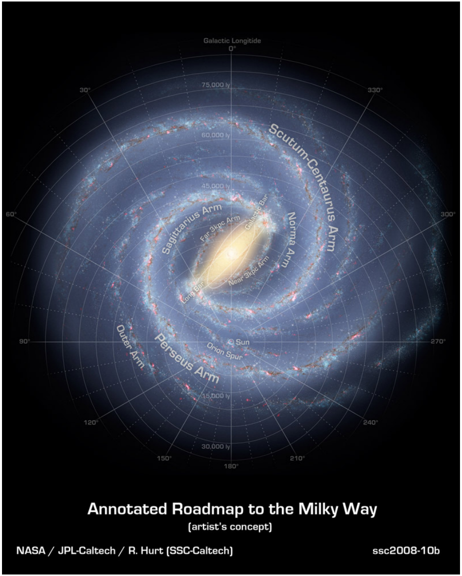
- Our galaxy, the Milky Way, appears to us as a faint band of diffuse light stretching across the sky (if there are no street lights around....)
- It is paradoxically difficult to work out its structure, because we are inside it. Dust obscures much or most of it from our view.
- First person to describe its structure accurately was Thomas Wright of County Durham (but Immanuel Kant often gets the credit)

The Milky Way

The Milky Way

- The Milky Way is a *spiral galaxy*. It consists of a central bulge, with several arms of stars and gas winding outwards from it.
- It is about 100,000 light years across.
- We are about two thirds of the way out from the centre to the edge.

The Milky Way



The Milky Way

- There are about 200 billion stars in the galaxy ($2x10^{11}$). As well as stars, there are also bright nebulae and dark clouds of dust and gas.
- Many of the stars are in clusters, which come in two type: *open clusters* and *globular clusters*

The Milky Way

The Milky Way

The Milky Way

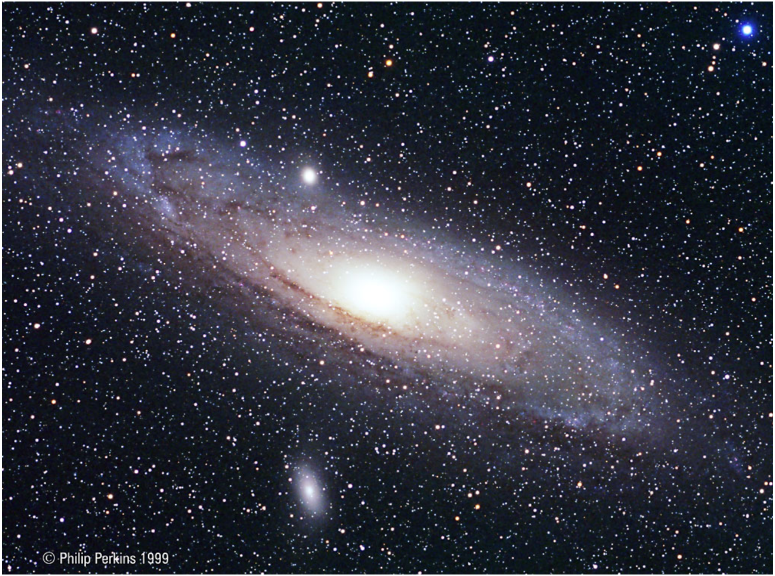
- Over millions of years, star clusters tend to disperse gradually.
- Many of the stars in the Plough are members of a dispersed star cluster. They continue to move through space in roughly the same direction.

Animation - available in screen version

Beyond the Milky Way

- Our galaxy belongs to the Local Group – a collection of about thirty galaxies at distances of up to about ten million light years.
- There are three large spiral galaxies in it: the Milky Way, Andromeda and Triangulum.
- Andromeda is the largest of the three.
- The rest of the galaxies are dwarf galaxies.

Beyond the Milky Way



Beyond the Milky Way

Beyond the Milky Way

Types of galaxies

- The three large galaxies in the local group are spiral galaxies.
- Spiral galaxies are either barred or non-barred

Types of galaxies

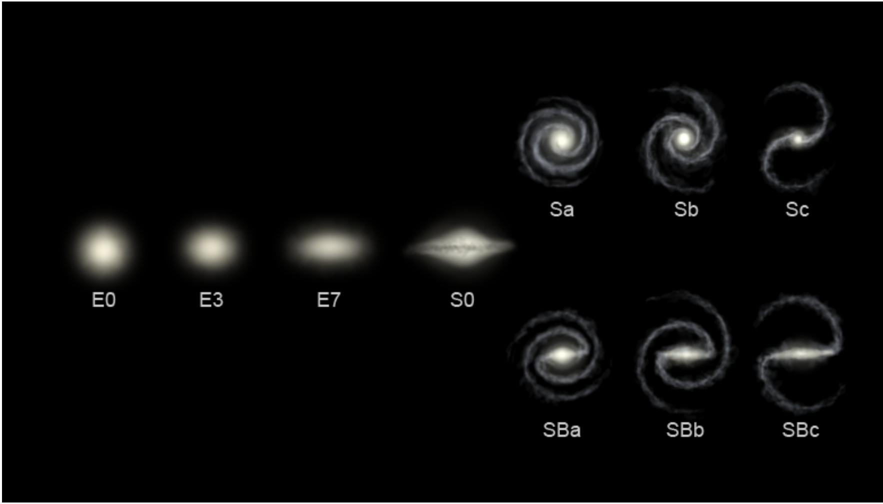
- Many of the smaller galaxies are elliptical galaxies.
- Ellipticals can be very large as well.

Types of galaxies

- Most small galaxies are irregular – they have no definable shape.

The ‘Tuning fork’ diagram

- Edwin Hubble presented galaxies on this sort of diagram:



The ‘Tuning fork’ diagram

- Hubble thought that this might represent an evolutionary sequence.
- He referred to elliptical galaxies as ‘early-type’, and spirals as ‘late-type’.
- This terminology is occasionally still encountered but in fact, ellipticals contain the oldest stars. Spirals are much younger

Galaxy types

- Elliptical galaxies are made of old, yellow stars.
- No new star formation is occurring, and no star-forming nebulae are seen.
- Spiral galaxies and irregular galaxies are sites of active star formation, sometimes extremely vigorous. Nebulae are common.

Galaxy types

- Ellipticals do not ‘evolve’ into spirals.
- The opposite can happen though...

Galaxy collisions

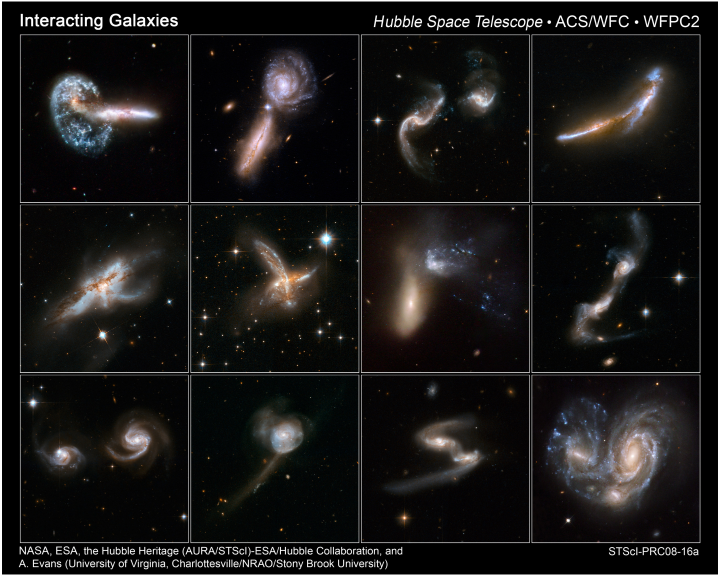
- A typical star is about 500,000km across, but the typical distance between stars is about 3 light years – 50 million times larger. If the Sun was a football in London, Proxima Centauri would be roughly in New York.

- Stars are following broadly circular orbits around the galaxy, all in the same direction.
- So, collisions between stars are extremely rare

Galaxy collisions

- For galaxies, the situation is different: for example, the distance from the Milky Way to the Andromeda Galaxy is about twenty times as large as the diameter of the Milky Way.
- If the galaxy was a football in this room, Andromeda would only be a few rows back.
- Motions within clusters are disordered
- So, collisions are very common.
- Collisions trigger massive bursts of star formation.
- If two spirals merge, then all the gas and dust is stripped, the structure is lost, and what emerges afterwards is an elliptical galaxy.

Galaxy collisions



Active galaxies

- Many galaxies contain vast amounts of matter (millions of times the mass of the Sun) in a very small region at their core (perhaps only a few light-hours across).
- Our galaxy is one such galaxy.

Active galaxies

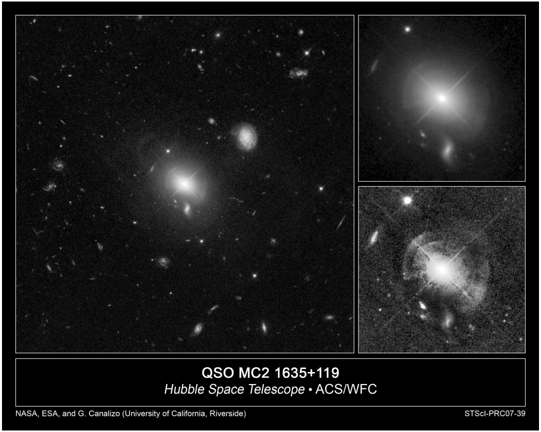
Animation - available in screen version

Active galaxies

- You can see that whatever is at the centre of the Milky Way is not emitting any visible light.
- It is thought to be a black hole – an object so massive that even light cannot escape its gravity.

Active galaxies

- Often, material orbiting a black hole gets so hot that emits extreme amounts of radiation.
- Quasars (Quasi-stellar objects) are some of the most luminous objects in the universe, and are powered by black holes.



Cosmic distances

- Discussed earlier that the most direct way to measure the distance to a star or other astronomical object is to measure its *parallax* – the small shift in its position over a year caused by the movement of the Earth from one side of its orbit to the other.
- This is only accurate out to a few hundred parsecs at best. So how do we find out the distances to objects further away than that?
- There is an elaborate set of interlinking distance measures which is used to work out the scale of the universe - the *cosmic distance ladder*.

Expansion parallax

- Compare plane-of-sky expansion with line-of-sight (Doppler) velocity: the Crab Nebula is at a distance of 2000+-500 parsecs.

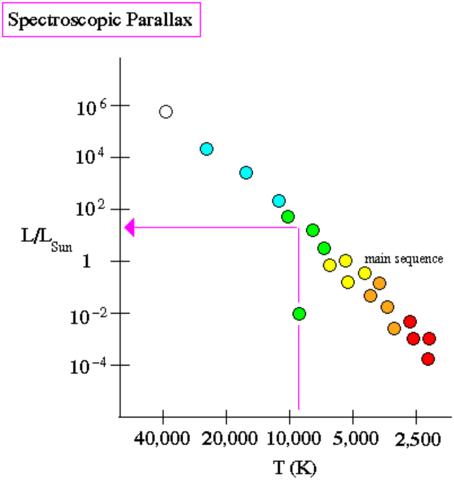
Expansion parallax

- Compare plane-of-sky expansion with line-of-sight (Doppler) velocity: the Crab Nebula is at a distance of 2000+-500 parsecs.

Spectroscopic parallax

- If we can work out the position of a star on the Hertzsprung-Russell diagram, we know its absolute magnitude, and therefore its distance.
- Temperature is easily determined, and therefore its luminosity can simply be read off from the diagram.
- This is known as *spectroscopic parallax*. It's not particularly accurate. And it's also not anything to do with parallax!

Spectroscopic parallax



the true brightness of a star can be found if the color is known by matching the star to the main sequence. Knowledge of the observed brightness plus the true brightness derives the distance to the star.

Main sequence fitting

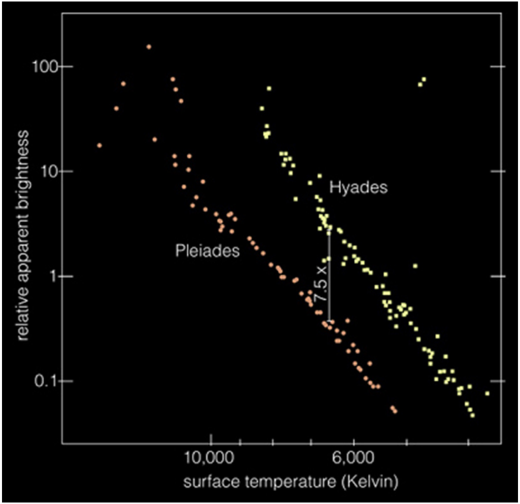
- More useful than the spectroscopic ‘parallax’ is *main sequence fitting*. If we observe a cluster of stars, and plot an HR diagram using apparent magnitude and temperature, we will see the main sequence.
- The distance to the cluster is then easily determined from the difference between the apparent magnitude of its main sequence, compared to the absolute magnitude of the standard main sequence.

Main sequence fitting

- Example: Pleiades and Hyades - two nearby well-known star clusters.
- On an HR diagram, we see that the main sequence of the Hyades is about 7.5$\times$ brighter than the main sequence of the Pleiades.

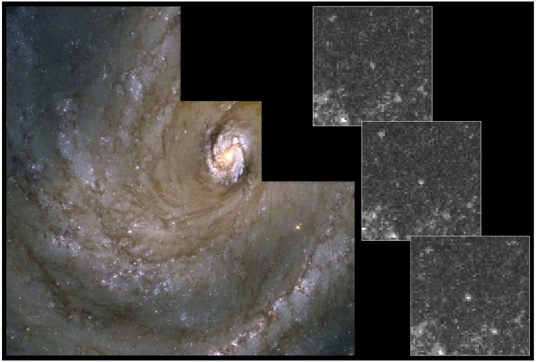
Main sequence fitting

- From the inverse square law, this means that the distance to the Pleiades is $\sqrt{7.5} = 2.7$ times the distance to the Hyades.



Standard candles

- As discussed earlier, many evolved stars go through phases where their brightness is variable. A very useful type of variable star is called a *cepheid variable*, named after δ Cephei, the first known example. The Pole Star is also a cepheid



Standard candles

- Cepheids brighten and fade extremely regularly over periods ranging from a few hours to a few weeks.
- They are are extremely useful because it turns out that their luminosity and period are tightly related – the longer the period, the brighter the Cepheid.
- The brightest cepheids are many thousands of times brighter than the Sun. This means they can be seen out to large distances – as far away as 60 million light years.

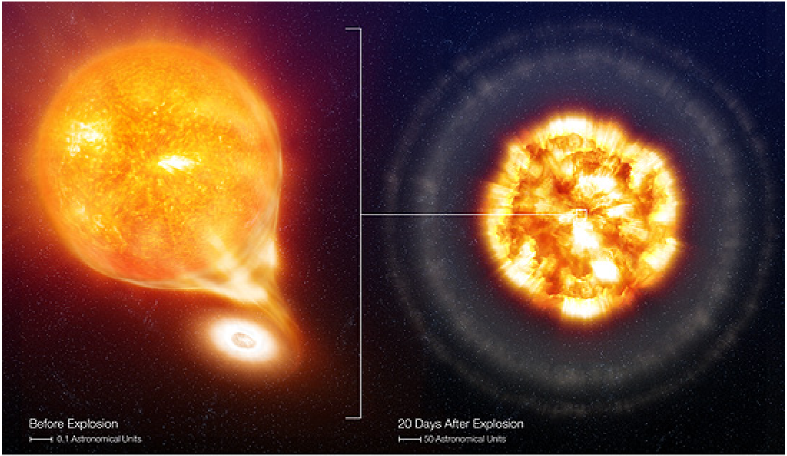
Cepheid variables

- Cepheids answered some major questions in astronomy: Shapley observed them in our galaxy and determined its size.
- Edwin Hubble observed cepheids in the Andromeda Galaxy, and thus showed that it was outside our own galaxy.
- One of the main aims of the Hubble Space Telescope was to observe cepheid variables in distant galaxies, to refine the cosmic distance scale.

Standard candles

- Cepheids are one of the most important of the *standard candles* – objects whose absolute magnitude is known and so whose distance can easily be found.
- Other examples of standard candles are:
  - RR Lyrae stars (similar to Cepheids but less luminous)
  - planetary nebulae
  - Type Ia supernovae
- We talked about core-collapse supernovae, which are the end result of the lives of very massive stars. These are also called Type II supernovae
- Type Ia supernovae result from binary system in which matter is flowing from a red giant onto a white dwarf.

Standard candles



SN 2006X, before and after the Type Ia Supernova Explosion
(Artist Impression)

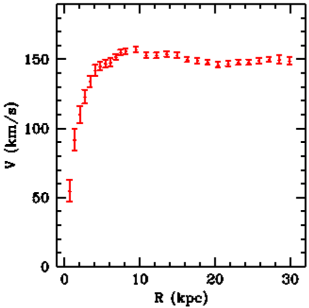
ESO Press Photo 31b/07 (12 July 2007)

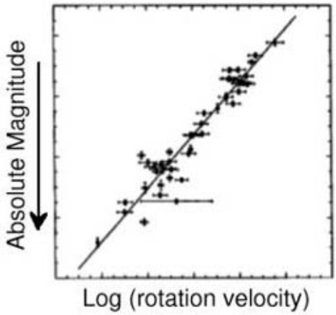
Standard candles

- As it gets heavier, the temperature in the white dwarf rises. When the white dwarf reaches a critical mass, the temperature is high enough to trigger sudden explosive nuclear fusion, and the star explodes violently.

Greater distances

- Using all these distance measuring techniques, the distances to many relatively nearby galaxies have been found.
- It has been found that the *faster* the stars in a galaxy are orbiting the centre, the *brighter* the galaxy is. The relationship between rotation and luminosity is called the Tully-Fisher Relation





Hubble flow

- Edwin Hubble was the first to find (using cepheids) that all external galaxies (except the ones in the Local Group) are receding, and that the velocity of recession is proportional to the distance.

$$v = H_0 D$$

- H_0 is a constant, with units of km/s/Mpc, called the Hubble Constant. It is one of the most important numbers in astronomy.

Hubble flow

- Using all the distance indicators discussed eventually allows us to estimate the Hubble Constant. The generally accepted value is about 70 km/s/Mpc.
- Once it is known, then for very distant galaxies, measuring the redshift gives us an idea of the distance.