Chapter 13 – The Deaths of Stars

On July 4, 1054, Chinese astronomers noted a new bright star in the constellation of Taurus. The "guest star" was so bright it could be seen in daylight for almost a month! This event was recorded by several independent chinese astronomers and could be observed for almost 2 years.

This dramatic event heralded the death throes of a massive star only 6500 light years away. When we turn modern day telescopes towards Taurus we observe the fallout from this immense explosion. This region is known as the Crab Nebula (M1).

Located inside the nebula is a pulsar – a fast rotating neutron star, the final dense remains of the star that went supernova only a millenium ago...

As with many properties of stars that we have seen, how a star ends its life depends on its mass. The common feature across the mass range is that stars “die” when they run out of fuel, because now there is no way to resist the compression force of gravity.

The Death of Low Mass Stars

The core of a star heats up in response to gravitational contraction. Therefore, low mass stars never get very hot. In fact, stars below 0.4 solar masses only get hot enough to fuse hydrogen (and only in p-p chain reactions).

This low temperature means that the hydrogen fuel is consumed relatively slowly.

In addition, as we saw in a previous lecture, very low mass stars are completely convective. The large scale convection continually brings fresh hydrogen fuel to the centre of the star.

This supply of fresh material insures an even longer life of a low mass star

Another consequence of this convective mixing is that, unlike more massive stars, low mass stars don't form a helium core. This means they never become giants.

The Death of Sun-like Stars

As we have seen in previous lectures, stars betwen about 0.4 and 4 solar masses burn H in to He and then He into C via the triple alpha process. The formation of a He core causes them to become giants. However, these stars are not hot enough to fuse C. We know that the sun is already shedding mass at a very low rate via the solar wind. When a star reaches the giant phase, it can lose mass in much larger quantities. This can be due to one of (at least) 3 reasons:

1) Because the gravity at the surface of a puffed up giant is very weak, the normal mass loss through stellar winds can be exagerated

2) Giant stars of a few solar masses are very cool, only about 2000K. Some giants get so cool that grains of dust like soot can form in their atmospheres. These grains get physically pushed out of the star, also causing mass loss.

3) Because the triple alpha (like all nuclear reactions) is very temperature sensitive, so there may be periodic eruptions in the He-burning shell. This causes a thermal pulse which can cause eruptions of energy, lifting shells of gas from the photosphere of the star.

These processes can significantly alter the mass of a star (by a solar mass or more), enough to change its destiny on the HR diagram.

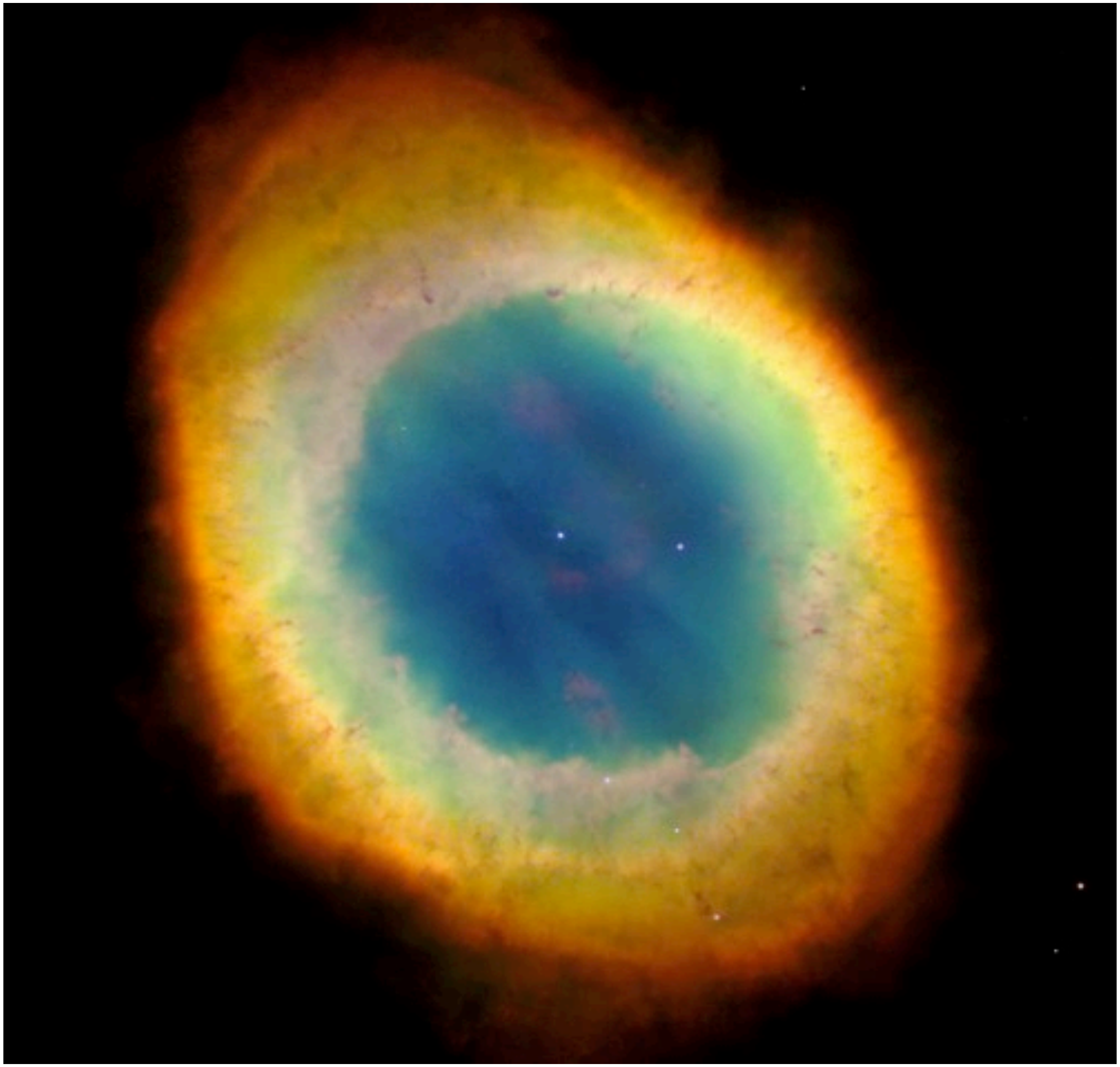
Mass loss from even sun-like stars can result in dramatic consequences...

The Eskimo nebula (photographed here by Hubble) is a sun-like star in its late stages. It began shedding material about 10,000 years ago.

Planetary Nebulae

Not to be confused with the nebulae we considered as places of star birth, planetary nebulae (PN) are formed when mid-sized stars shed a layer of their skin.

Planetary nebulae have nothing to do with planets! Sometimes when viewed through small telescopes PN can look like the coloured disk of a planet, but this is a complete misnomer.

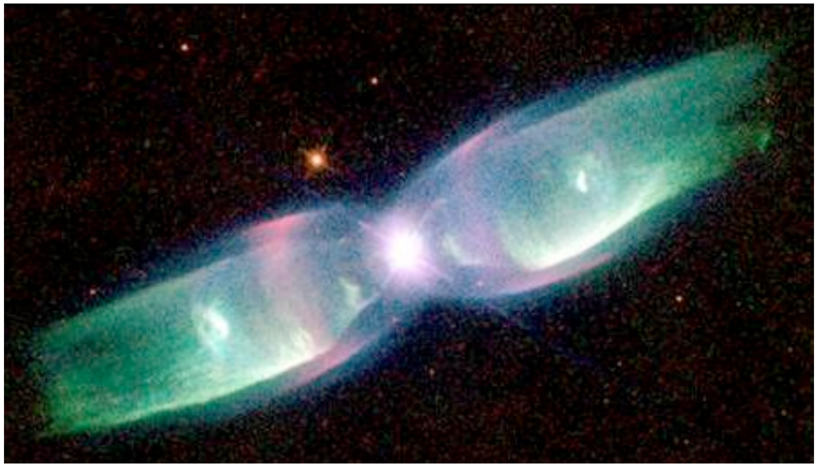


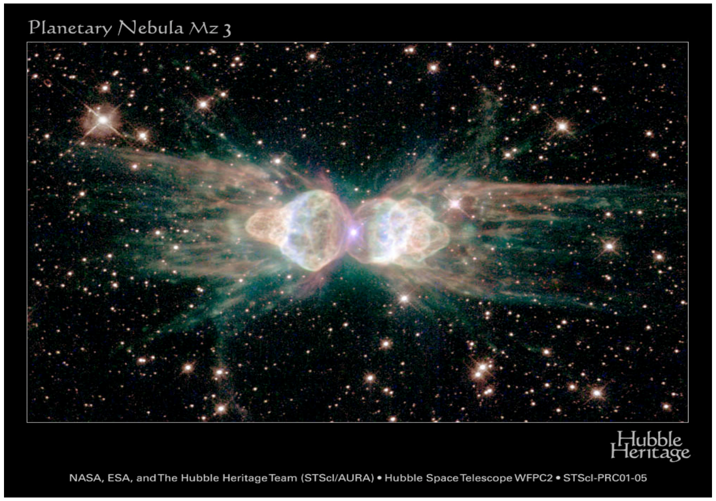
Some Properties of Planetary Nebulae

The spectra of PN contain emission lines, so we know that the gas is low density.

These emission lines are Doppler shifted by up to ~20 km/s, which tells us that the gas is expanding. PN nebulae form from stars with masses about 1-8 solar masses that leave a hot white dwarf behind. Dividing the radius of the nebula by its expansion velocity gives us its age. Most PN are 1000 – 10,000 years old.

Planetary nebulae are often not spherical. Some PN have jets or rings.





How are these elaborate shapes and colours formed? The colours come from ionized gas which is being lit up by the hot interior of the star, which is all that remains once it has cast off many layers of its surface. The central (WD) star must be hotter than about 25,000 K to cause a PN to glow. Jets are formed if some of the previously expelled gas forms a disk around the star, perhaps in a binary system. Subsequent ejections are funnelled out in bipolar jets (similar to the physics that produces jets in HH stars).

Example:

In a spectrum of the ring nebula, we find that the Balmer H alpha line is shifted from its rest wavelength of 656.3 nm by 0.04 nm. How old is the nebula (remembering that we calculated the diameter to be 1.7 lightyears)?

We have to do this problem in several stages.

1). Calculate the radius of the nebula. This is the easy bit, radius=diameter/2. So the radius is 0.85 lightyears.

2) Calculate the expansion velocity. To do this, we use the shift in wavelength of the emission line which is caused by the Doppler shift.

$$\frac{\text{velocity}}{\text{speed of light}} = \frac{\text{change in wavelength}}{\text{original wavelength}}$$

So, velocity = (0.04/656.3) x 300,000 = 18 km/s

3) Finally, to get the time required for the bubble to grow, we use time=distance/velocity. However, we first have to convert the distance (0.85 lightyears) into km. 1 ly = 9.5×10^{12} km, so 0.85 lyrs = 8×10^{12} km.

$$\text{time} = 8\times10^{12} / 18 = 4.4\times10^{11} \text{ seconds}$$

So the age of the nebula is about 4×10^{11} seconds, or about 14,000 years.

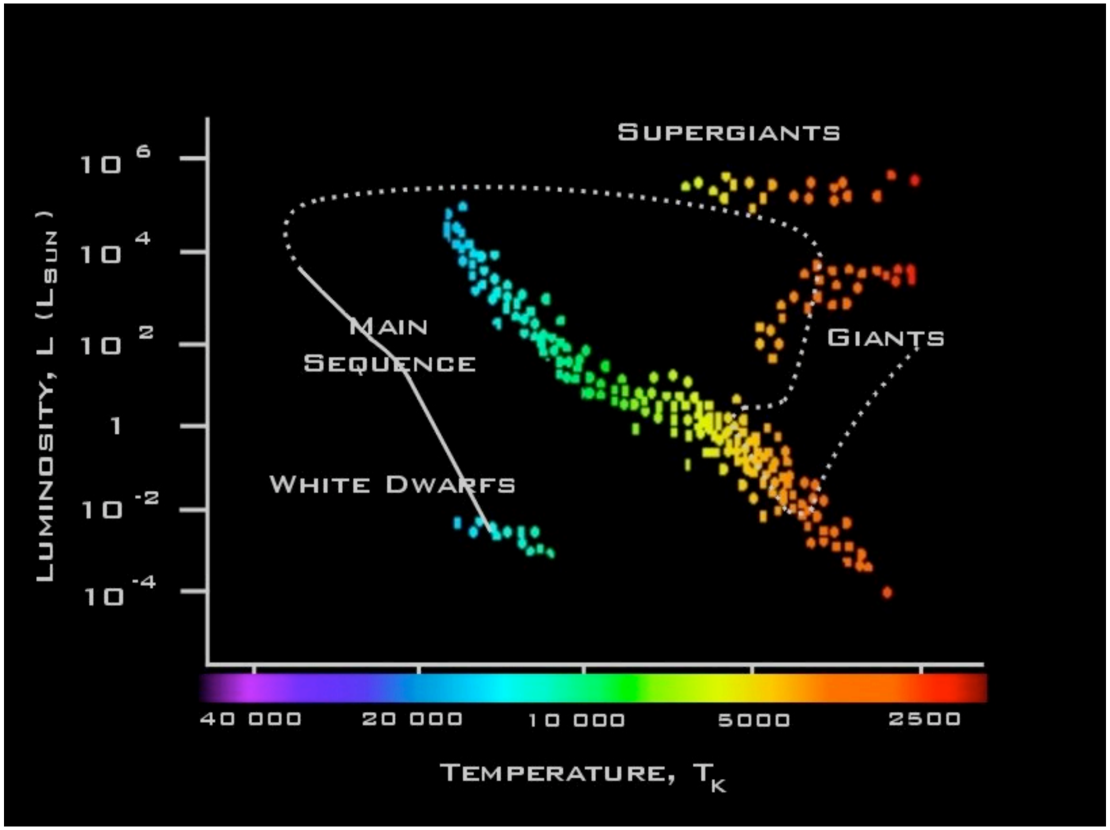
The White Dwarf Phase

Most medium mass (a few solar masses) stars will become PN, and this is a sign that they're nearing the end of their lives. Higher mass stars usually can't produce winds strong enough to “win” over their gravity.

After the PN phase, all that is left of the star is the carbon-oxygen core (the waste products of the triple alpha process that fuses He) surrounded by the helium and hydrogen shells. Remember that stars of a few solar masses get hot enough to fuse H and He via the p-p chain/CNO cycle and the triple alpha process, but they are not hot enough to burn carbon or oxygen.

After the PN phase, the star is very hot, so it makes a rapid progression from the giant/supergiant part of the HR towards the left. However, the central star eventually cools and migrates down to the white dwarf region of the diagram.

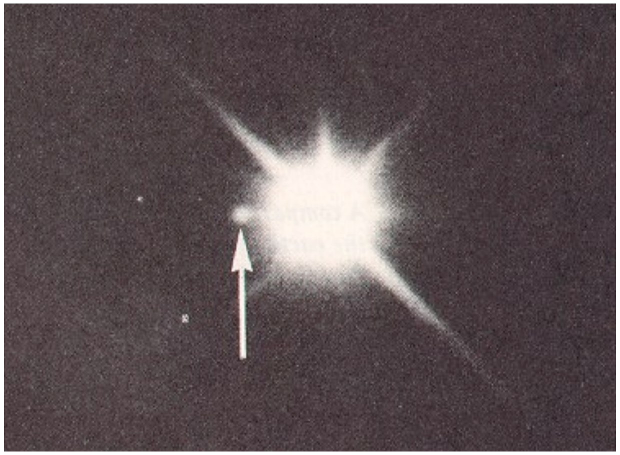
So it is as white dwarfs that most stars of a few solar masses will end up: with C and O choking the core and halting fusion....

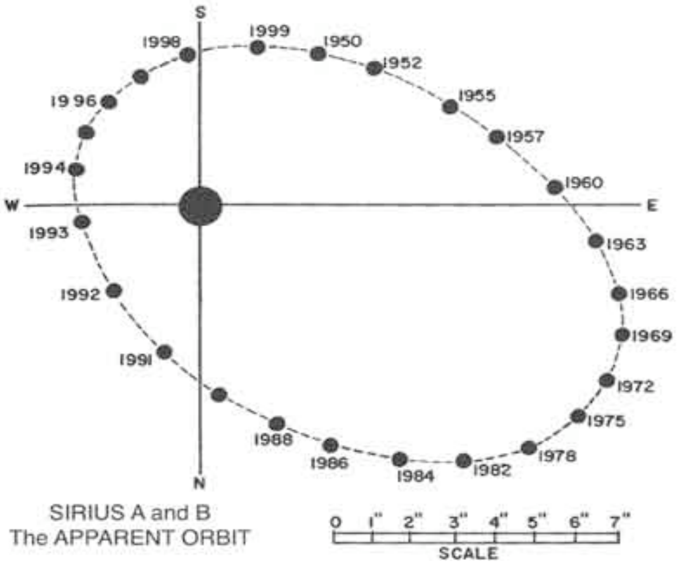


White Dwarfs and Degenerate Matter

As we have seen, the fusion of He into C and O is the end of the line for sun-like, medium mass stars (up to about 8 solar masses). The creation of PN is their last burst of glory before they become white dwarfs and start to fade.

WDs are quite common, since they are the graveyard for medium mass stars, but they are faint so not easy to detect. The first WD to be discovered was Sirius B, a faint companion to Sirius, the brightest star in the sky.





Observations of the orbits of this binary star system allow us to calculate the mass of Sirius B to be 1.2 solar masses.

The blue-white colour of Sirius B tells us that it is very hot (about 25000K), but the low luminosity tells us it must have a small surface area.

The Chandrasekhar Limit

WDs have essentially "burned themselves out" since even under great gravitational pressure they can not get hot enough to fuse carbon. Lack of internal pressure means there is nothing to oppose gravity which compresses the gas until it becomes degenerate.

In the 1920s, the brilliant Indian astrophysicist Subrahmanyan Chandrasekhar calculated the relationship between mass and radius in degenerate matter objects. This is work that would eventually win him the Nobel prize in 1983.

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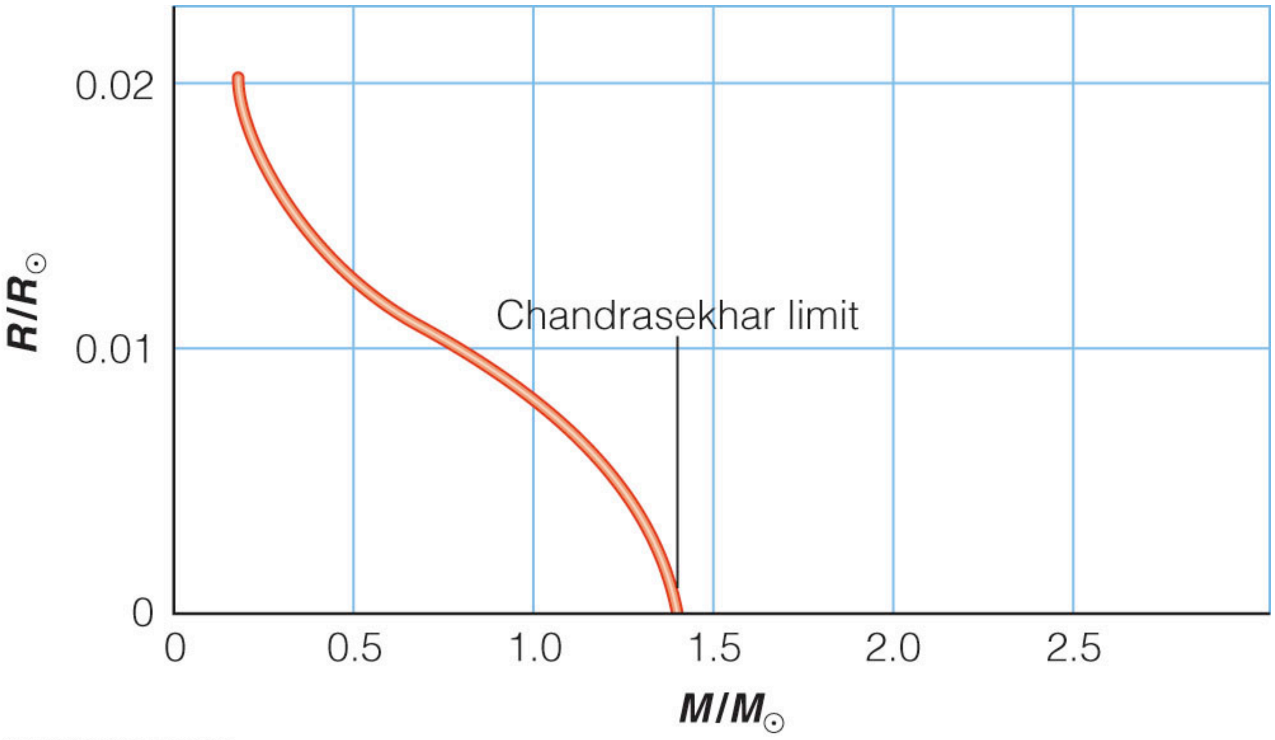
All that mass packed into a small space means the density is very high – about 3 million g/cubic cm. A teaspoonful of WD material would weigh about 15 tons on Earth! Put another way, a beach ball made of it WD matter would weigh the same as a cruise ship.

The Chandrasekhar Limit

Chandrasekhar found that the radius of a WD shrinks as mass is added to it and that the maximum mass of star that could form a WD was 1.4 solar masses. This is known as the Chandrasekhar limit. Beyond this limit, objects would instead become neutron stars or black holes.



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Because WDs don't create nuclear energy, they are not strictly stars. We refer to WDs and other degenerate entities as compact objects.

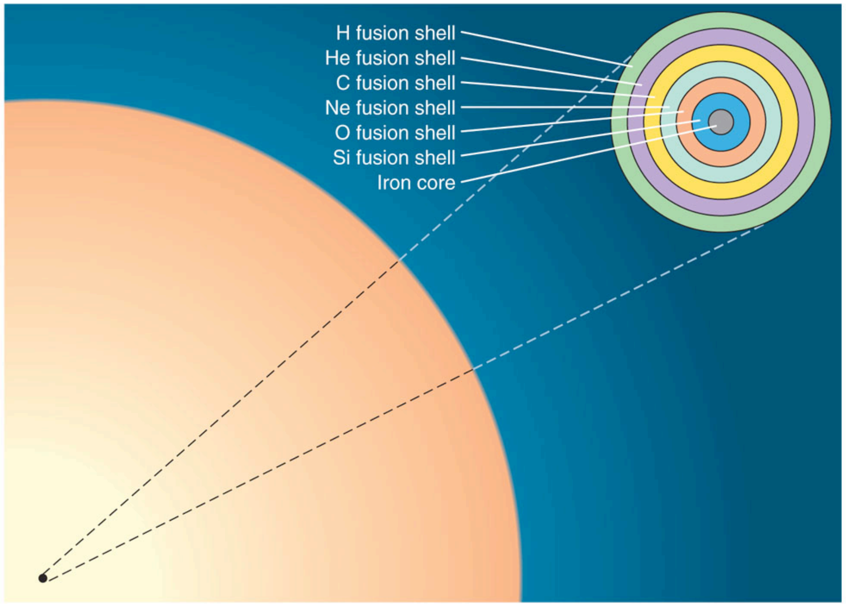
Despite the lack of an internal furnace, WDs are hot because of compression, so they have a lot of energy to radiate. Eventually, however, all of this will energy will have been radiated (it takes a long time though because of the small surface area) and the WD becomes a dead black dwarf.

The Death of Massive Stars

Although the final stages of their lives will be different from mid-mass stars, massive stars start out by burning H in their core (mostly through the CNO cycle), become supergiants and then fuse He via the triple alpha process. If a star still has > 4 solar masses when it gets to the giant stage, further reactions can occur in the core with concentric shells of burning around them. The waste from each nuclear reaction falls to the centre and if the temperature is high enough, that too can be "burned".

In this way, the full suite of chemical elements is built up in the core. In fact pretty much any atom in the universe that is lighter than iron (Fe) has been made in a star (heavier nuclei are created in supernova explosions). Elements are returned to the ISM in SN and are then recycled in subsequent generations of stars.

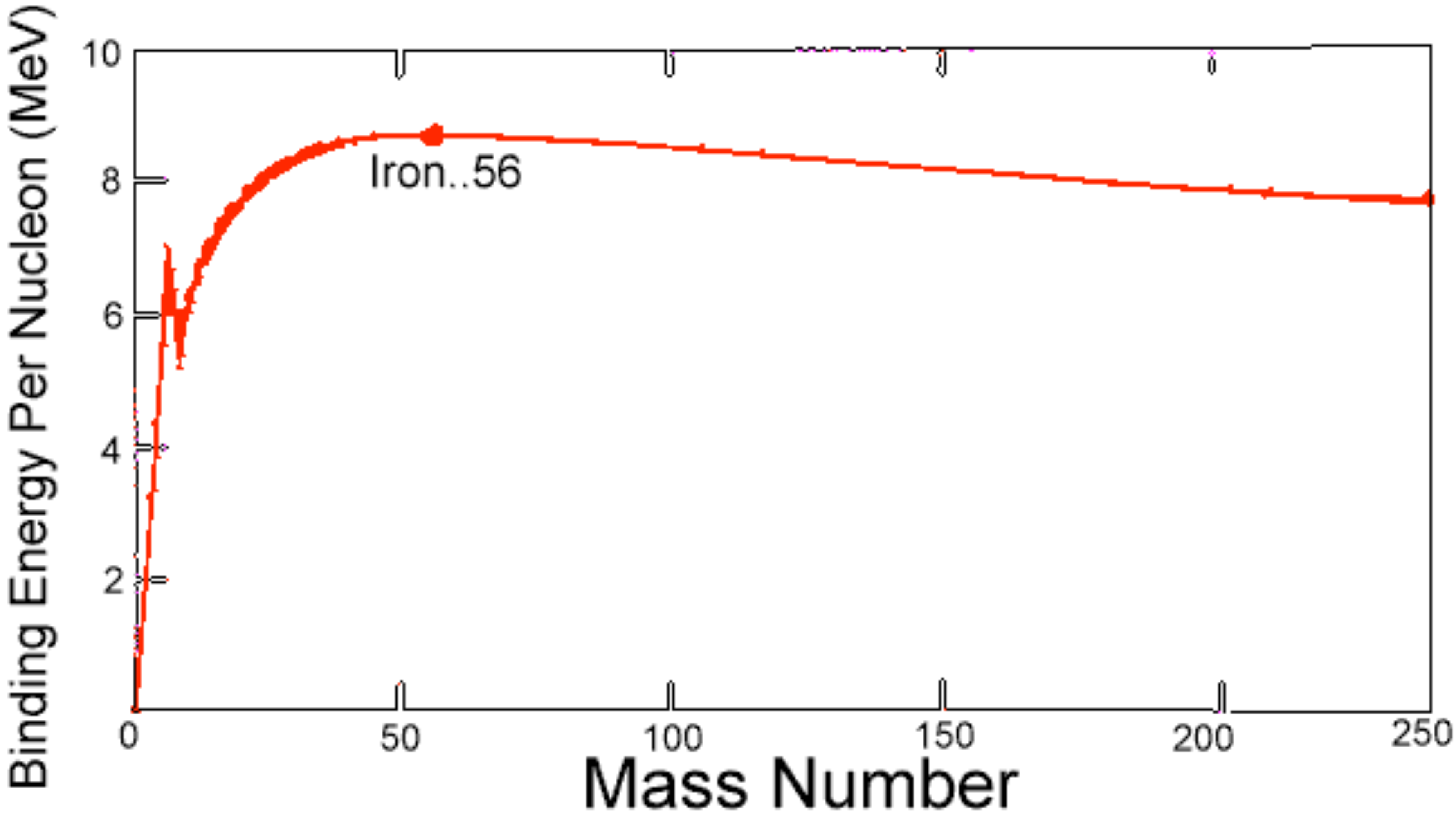
Later generations of stars have the heavy element content of the nebula from which they were formed.

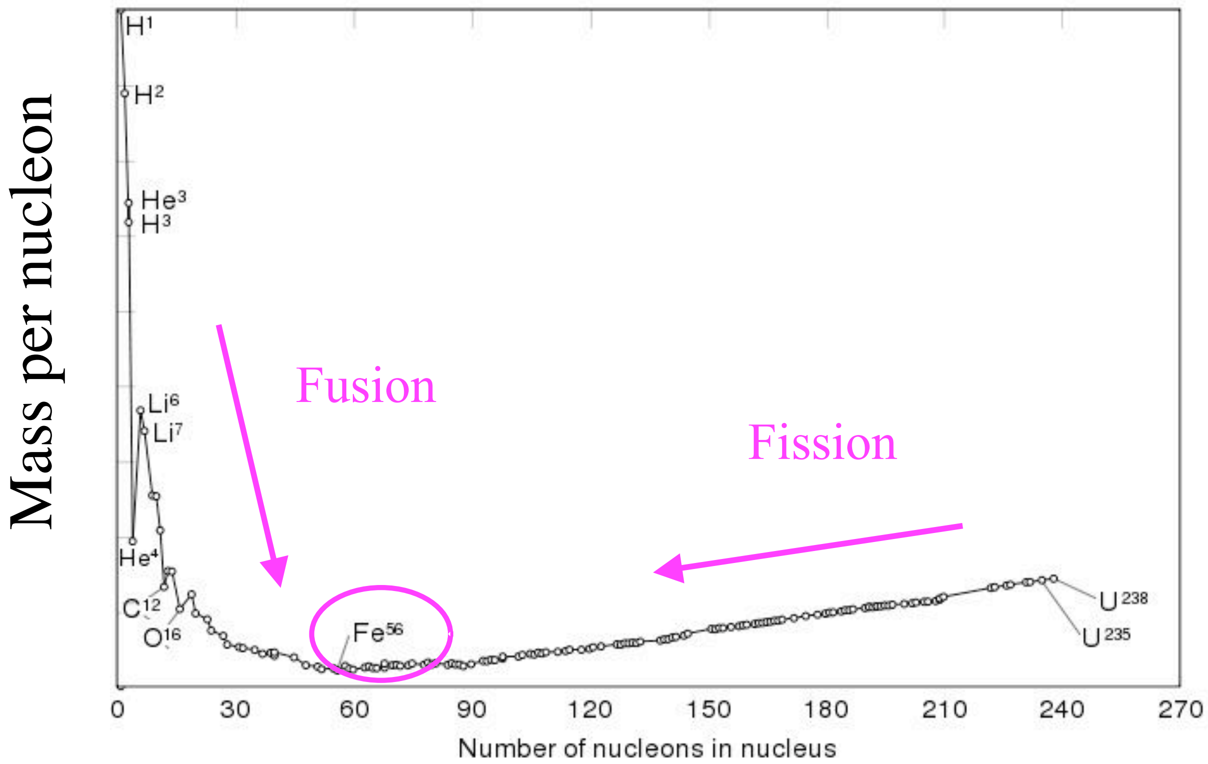


The heavier elements burn at increasingly rapid rates because they need to support the gravitational force with fewer nuclei. Also, fusion reactions of heavier elements release less energy per reaction. So whilst H burning lasts over 90% of the star's life, heavier elements burn for days or less.

Iron in a Star's Core – The End of The Road

In the section on the sun, we met the concept of binding energy. Low mass atoms produce energy via fusion (e.g. H in stars); massive particles produce energy by fission (e.g. Uranium).



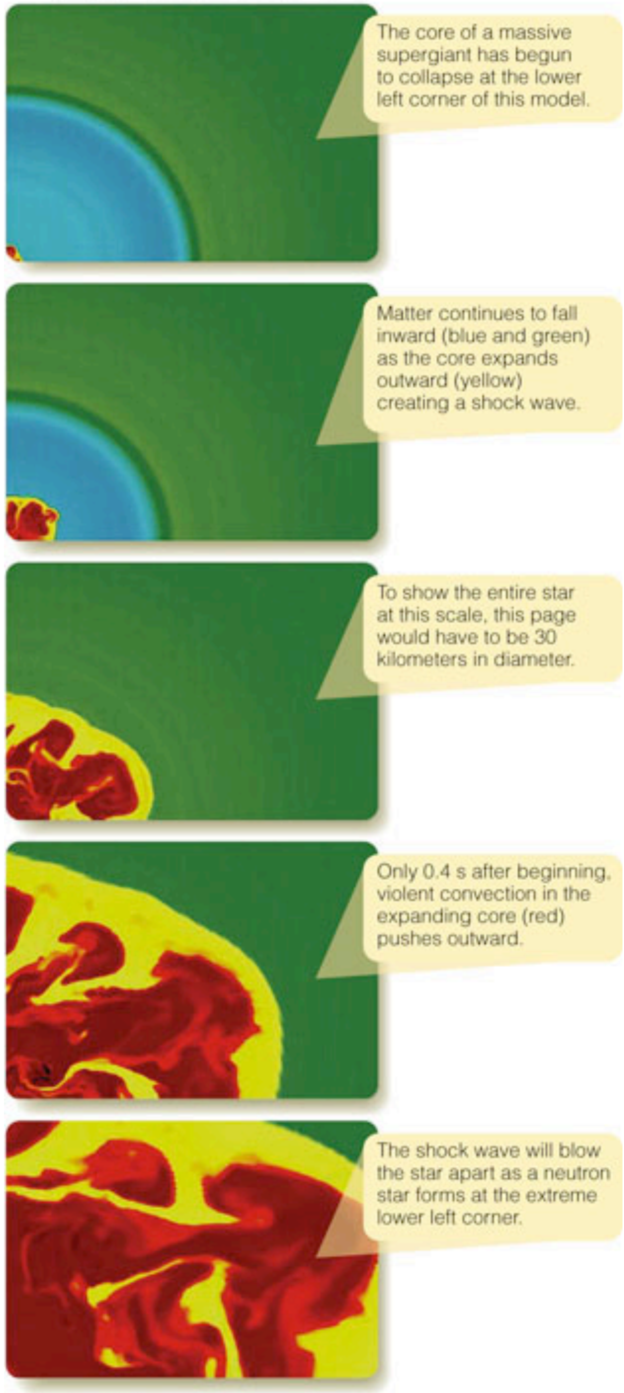


Another way of looking at this is to plot the mass per nucleon (where a nucleon in the nucleus, I.e. proton or neutron). When the light elements fuse, the "average" mass of a nucleon decreases. That lost mass has been converted to energy.

When heavy nuclei fuse, the same thing happens: the average mass of its nucleons decreases because some of the mass has been released to make energy. Iron lies at the trough of this curve, so there is no nuclear process (fission or fusion) that can create energy from iron.

So, when a star has Fe in its core, there is no other way to make energy, so the surrounding layers of the star start to collapse. This heats some of the inner shells, fusing more light elements, but still nothing can be done with the Fe (and more Fe is being constantly made).

The Exploding Core of a Supernova



The core of a massive supergiant has begun to collapse at the lower left corner of this model.

Matter continues to fall inward (blue and green) as the core expands outward (yellow) creating a shock wave.

To show the entire star at this scale, this page would have to be 30 kilometers in diameter.

Only 0.4 s after beginning, violent convection in the expanding core (red) pushes outward.

The shock wave will blow the star apart as a neutron star forms at the extreme lower left corner.

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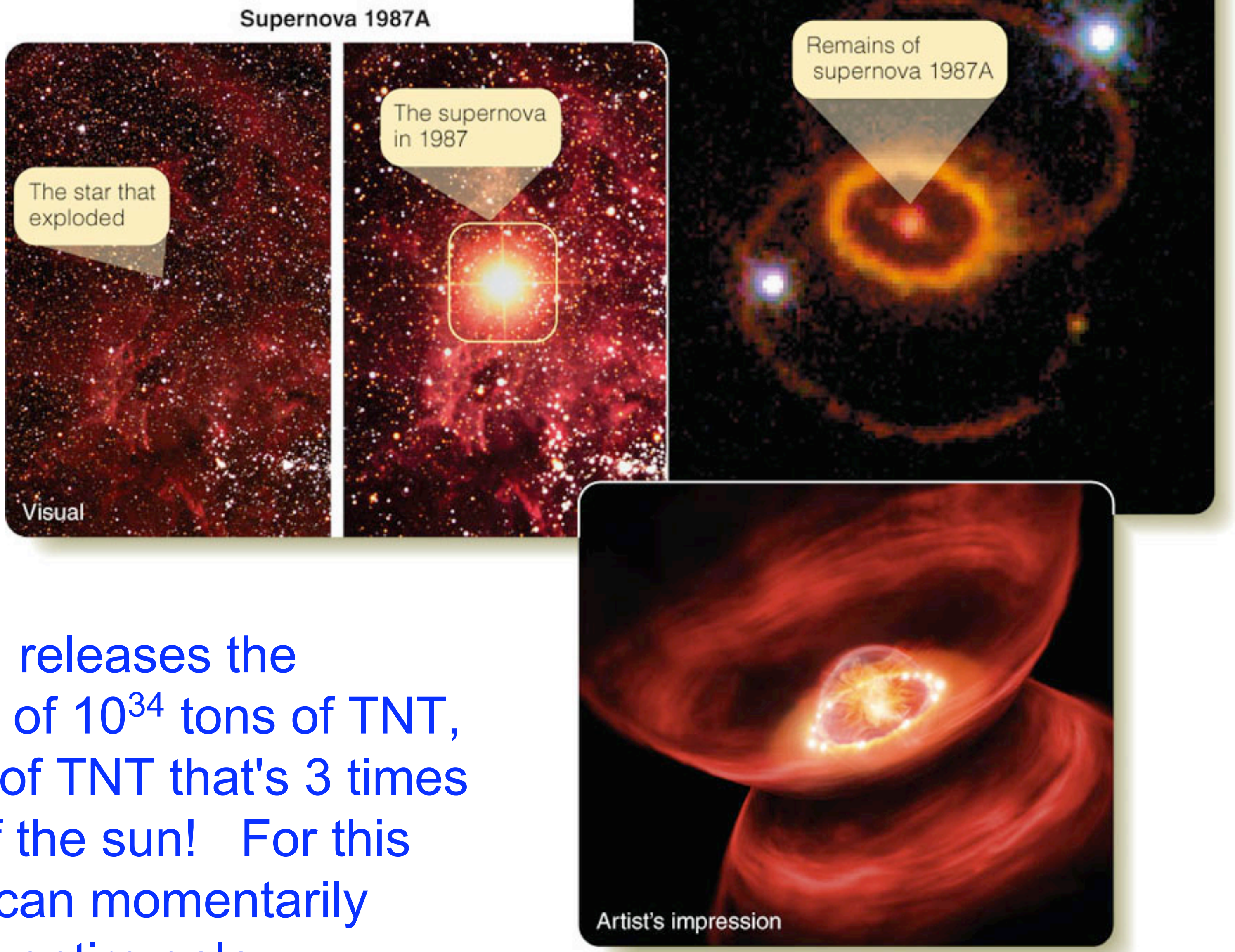
Once the core reaches 1-2 solar masses, it collapses under its own weight, a process which takes a fraction of a second. This event, known as a supernova, can be observed relatively regularly (many each year) in other galaxies, but only happen every few hundred years in our own galaxy.

The Fe core of a massive star collapses very fast creating a very high density core. A shockwave travels outward from the core and a high flux of neutrinos (which comprise 99% of the energy released in the core collapse). Together with the turbulence in the dense core this causes the star to explode.

Supernova 1987A in the LMC



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A single SN releases the equivanlent of 10^{34} tons of TNT, i.e. a mass of TNT that's 3 times the mass of the sun! For this reason SN can momentarily outshine an entire galaxy

There are 2 main types of SN, imaginatively called Type I and Type II.

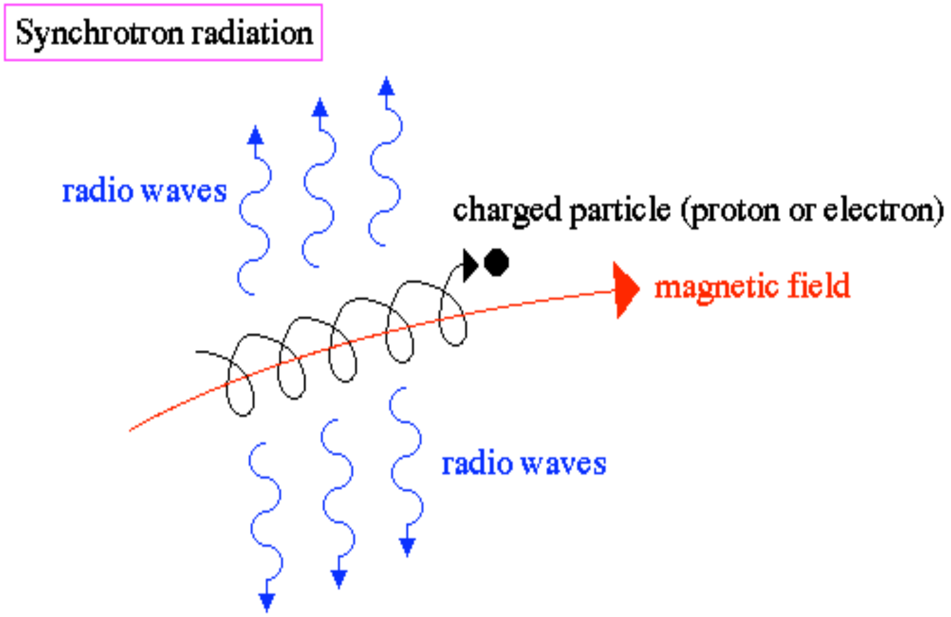
Type I: Have no hydrogen lines in their spectra. Probably formed as part of a binary system when a WD accreted matter from a companion. Original star probably lived about 1 billion years. Luminosity declines rapidly for a few months, then gradually.

Type II: Have hydrogen lines in their spectra. Originate from the death of a single massive star which has formed an Fe core and that lived for about 1 million years. Its luminosity declines in an irregular way.

About one SN happens per galaxy every century.

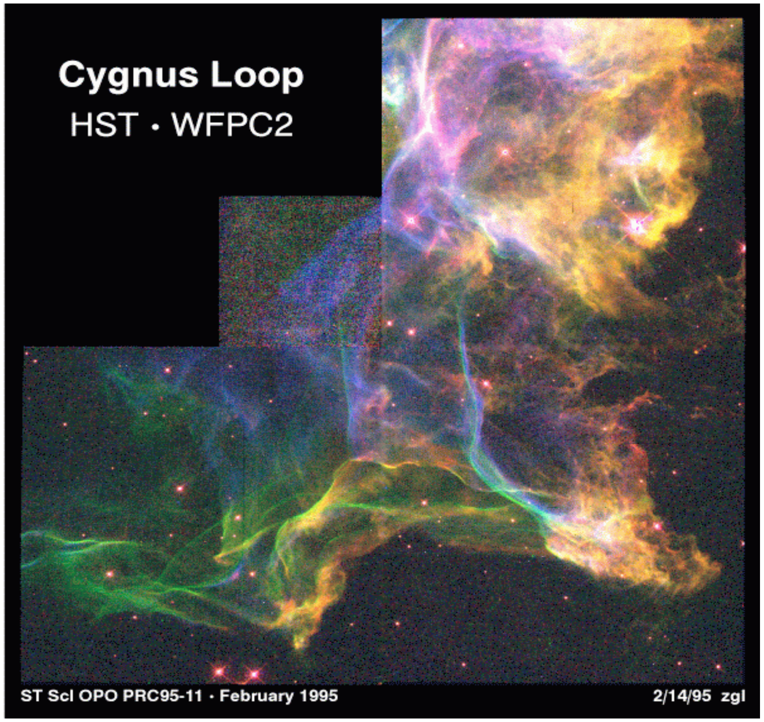
Supernova Remnants

Even when a Type II SN has faded, its remnant can be detected. The SN leaves behind a compact cinder, either a neutron star or a black hole, depending on the mass that is present.



synchrontron radiation occurs when a charged particle encounters a strong magnetic field – the particle is accelerated along a spiral path following the magnetic field and emitting radio waves in the process – the result is a distinct radio signature that reveals the strength of the magnetic field

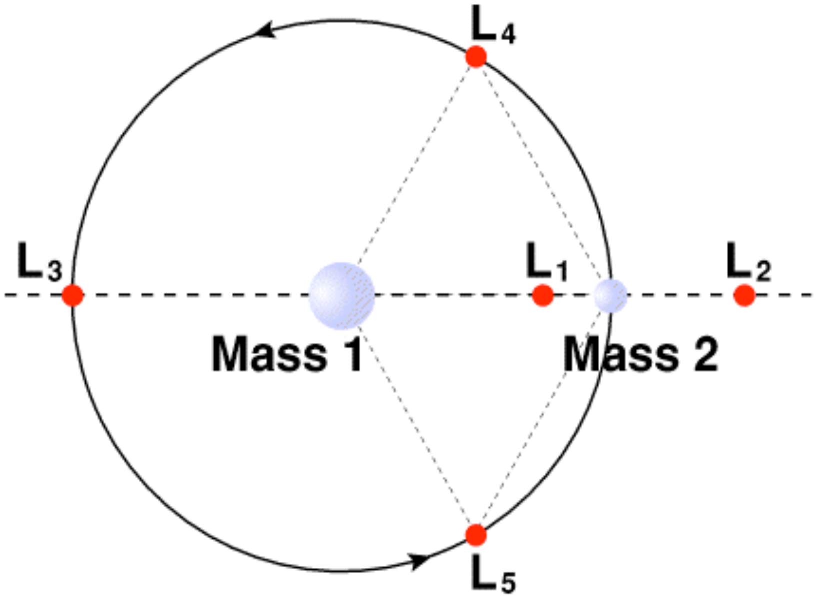
Whilst the SN remnant is young, it may be seen as glowing filaments of gas in the X-ray, but eventually this will fade. At cooler temperatures we can see it in the optical. We can also often detect the remnant radio wavelengths due to synchrotron radiation.



Evolution of Binary Stars

One final apsect of the late stages of stellar evolution that we will consider is the importance of companions, i.e. binary stars

An important concept when dealing with a two body system in astronomy is the Lagrangian points. There are 5 Lagrangian points in a binary system and they are places where gas is stable. Perhaps most importantly, the first Lagrangian points, L1, is where the gravitational effect from the two bodies is exactly equal.

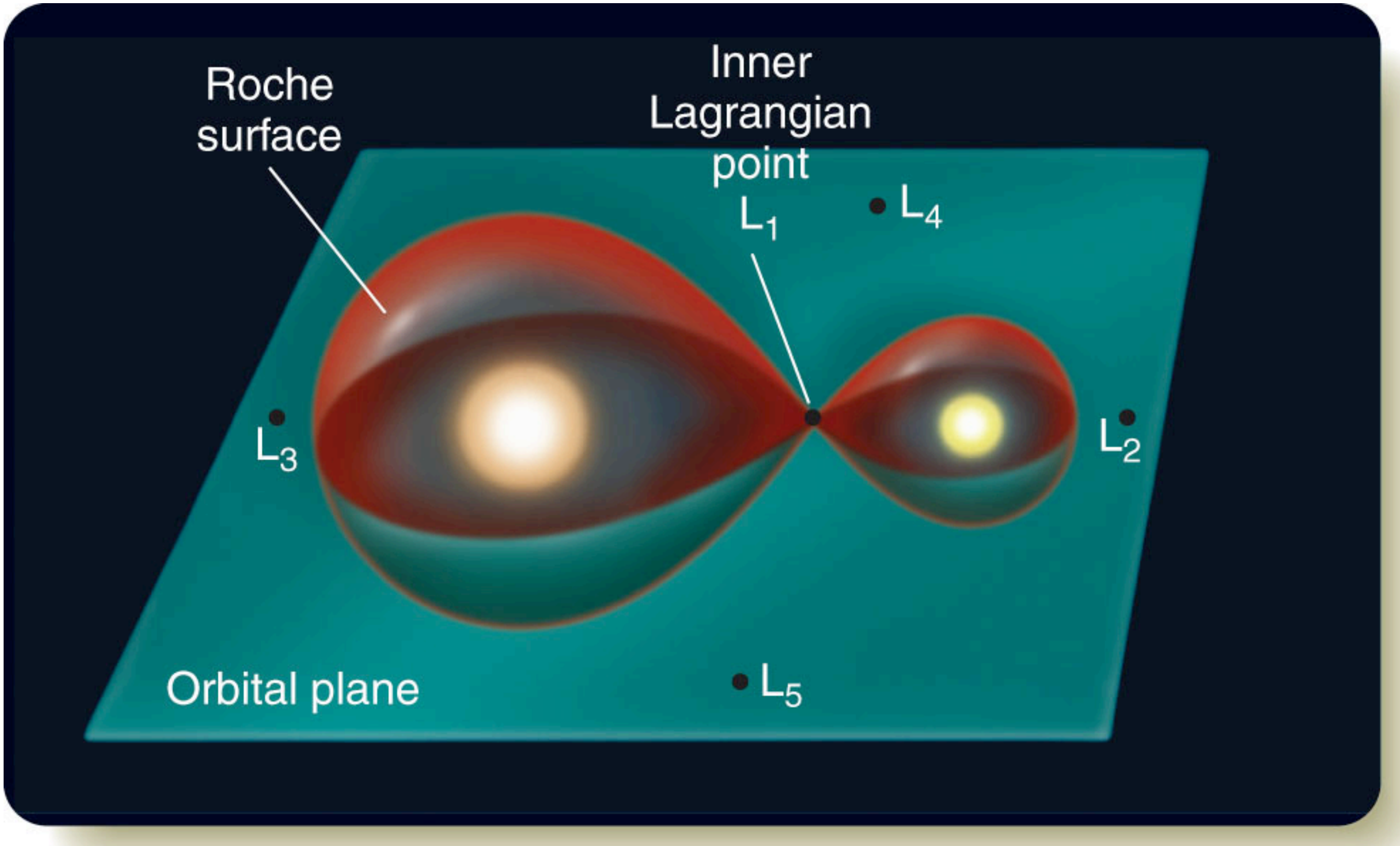


L1 is important because if mass is ejected from one star and crosses this point, it can be captured by the other star.

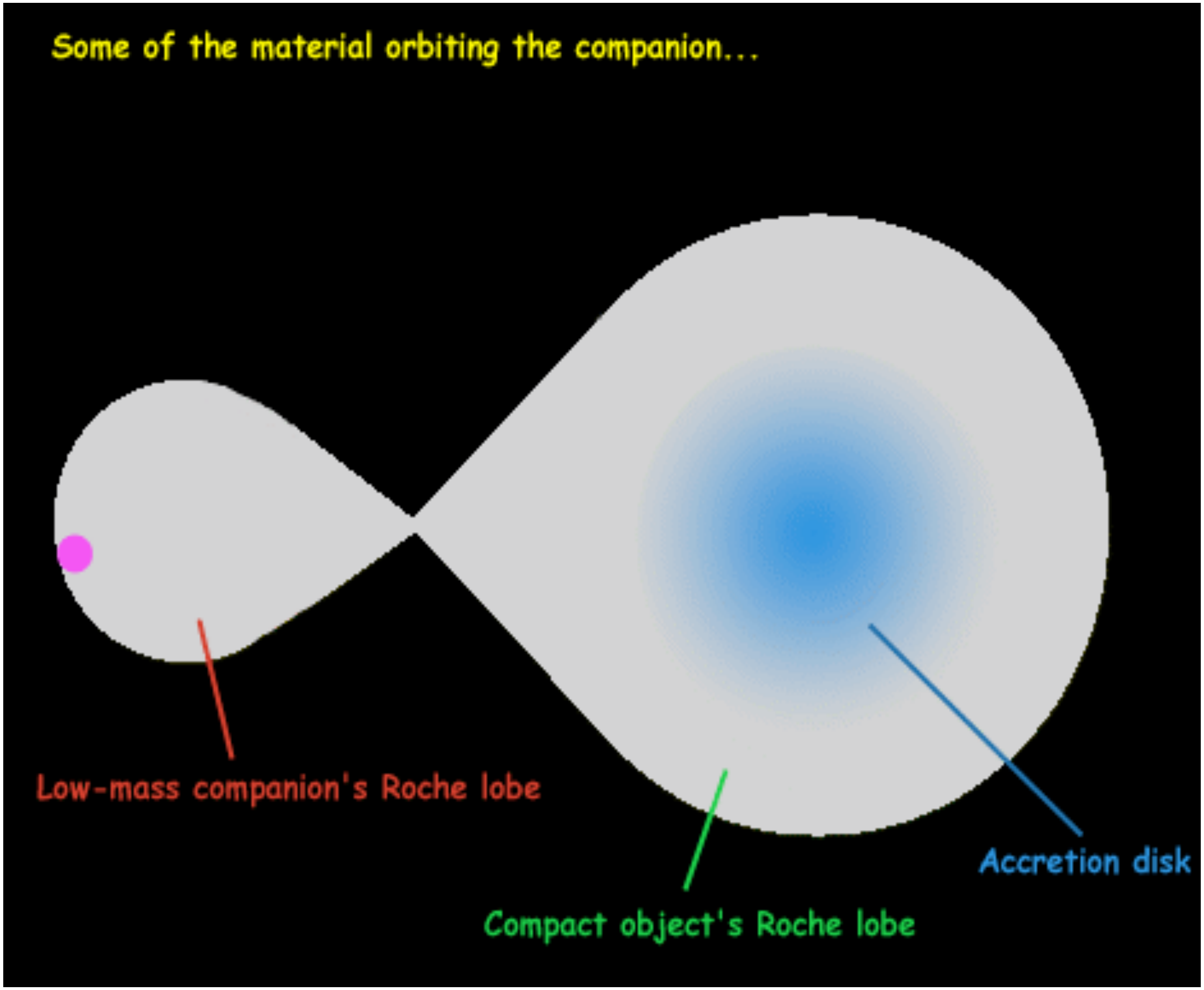
Such matter transfer can occur if one of the star's has a strong stellar wind, some material may cross L1. Alternatively, a star could grow large enough in its giant phase that it actually exceeds L1.

The Roche Lobes and Mass Transfer

We refer to the sphere of influence of each star in a binary as its Roche surface, or lobe. The pear shaped region shows which star's gravity affects a nearby particle. The 2 Roche surfaces meet at the stable L1 point.



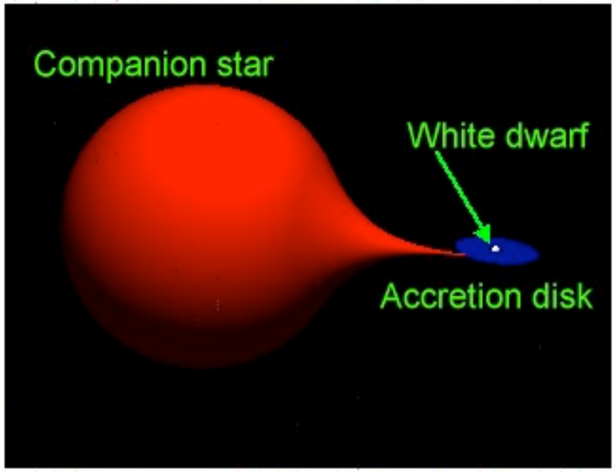
Mass can be transferred between objects if crosses over the stable inner point



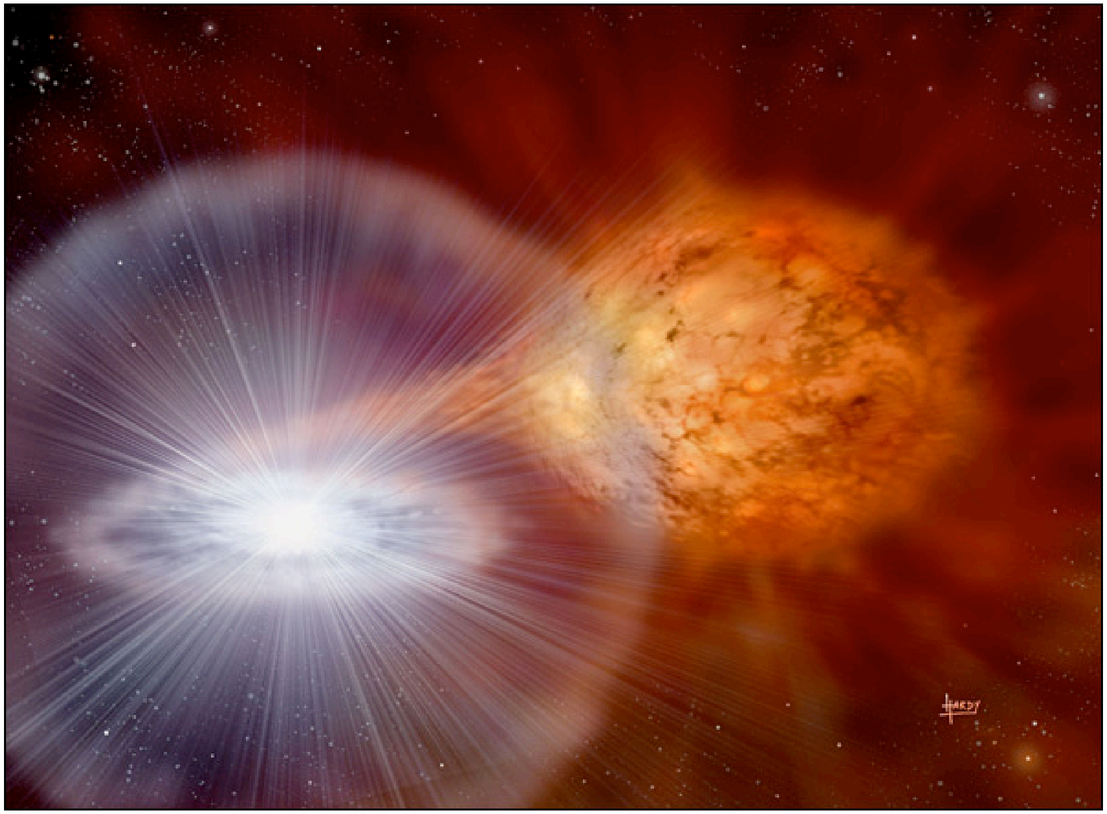
Type I Supernovae As Results of Mass Transfer

We have already seen that one cause of a supernova is when a very massive star forms Fe in its core. No more reactions can happen after this, so the core implodes and then sends a shock wave that rips through the star. This is a type II supernova

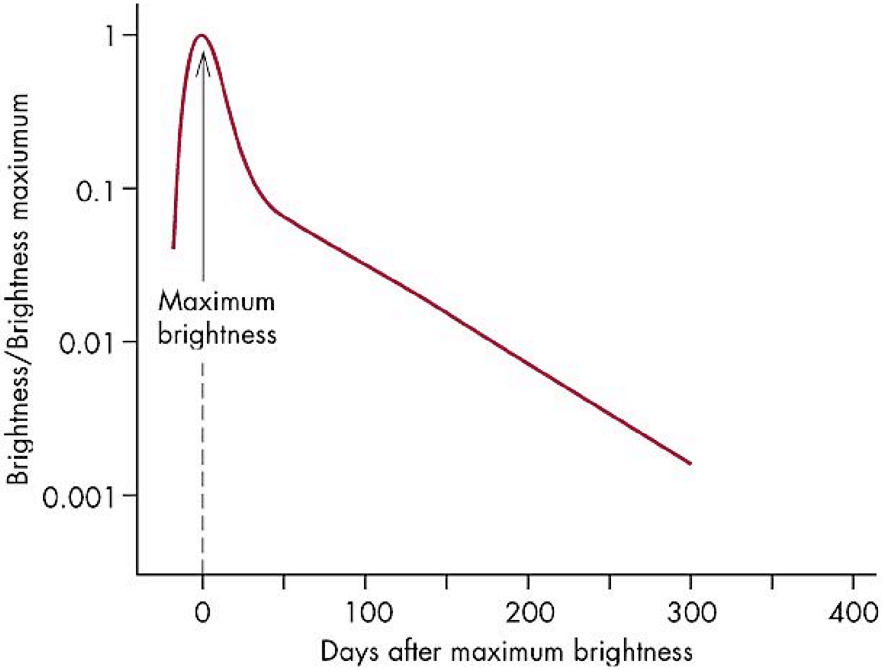
As we discussed, there is a second type of SN which does not have hydrogen lines. Although the progenitor and process of this type of SN (called a type Ia) is not well understood, the favourite theory is one of mass transfer onto a white dwarf from a a giant companion.



As material is transferred from the companion, it forms an accretion disk of hot material around the WD. Material in the disk heats up due to friction (which can be seen in X-rays), and losing energy as heat also sheds angular momentum so the material swirls down onto the surface of the WD.

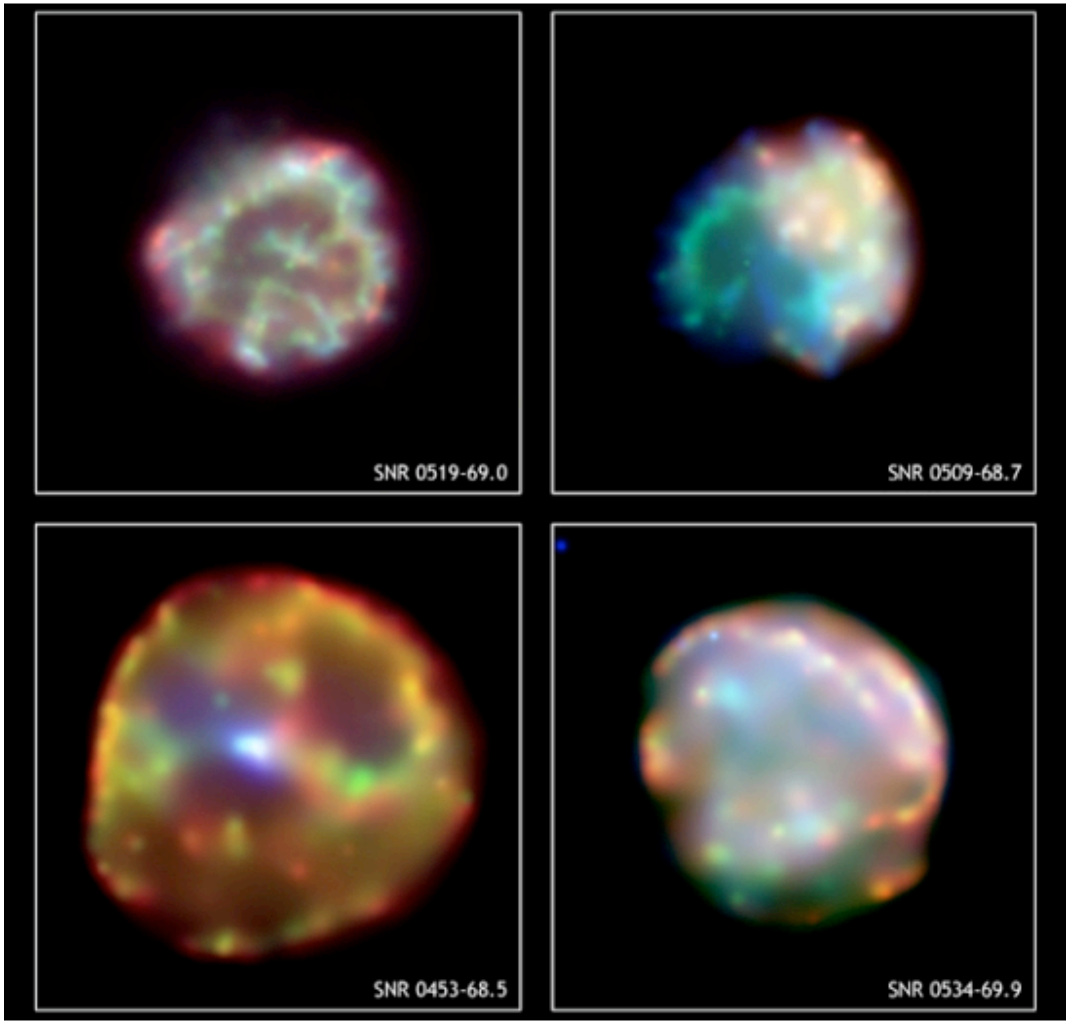


As material falls onto the WD it forms a layer of hydrogen above the degenerate surface. As this surface gets thicker, it becomes hotter and denser and eventually nuclear reactions are triggered on the surface. However, the gas density on the surface is so great that the material is degenerate, so that the pressure-temperature thermostat is broken when nuclear reactions start. It is like a helium flash runaway reaction, but on the surface. This causes a nova explosion which can recur many times without disturbing the WD. After a nova, the surface layer is cleared, but then starts to build-up again ready for the next outburst.



If material building up on the surface of the WD pushes it over the Chandrasekhar limit (1.4 solar masses) then it undergoes catastrophic collapse. Because the core of a WD contains usable fuel (unlike for a Type II SN) of carbon and oxygen, as it collapses and gets very hot, new nuclear fusion reactions are triggered in the core. However, because the material is degenerate, we again have a runaway reaction and the WD is entirely destroyed in a Type Ia SN. These supernova have the special property of all have approximately the same brightness, or absolute magnitude. Therefore, by measuring their apparent peak brightness, astronomers can compare this with the theoretical absolute magnitude and determine a distance.

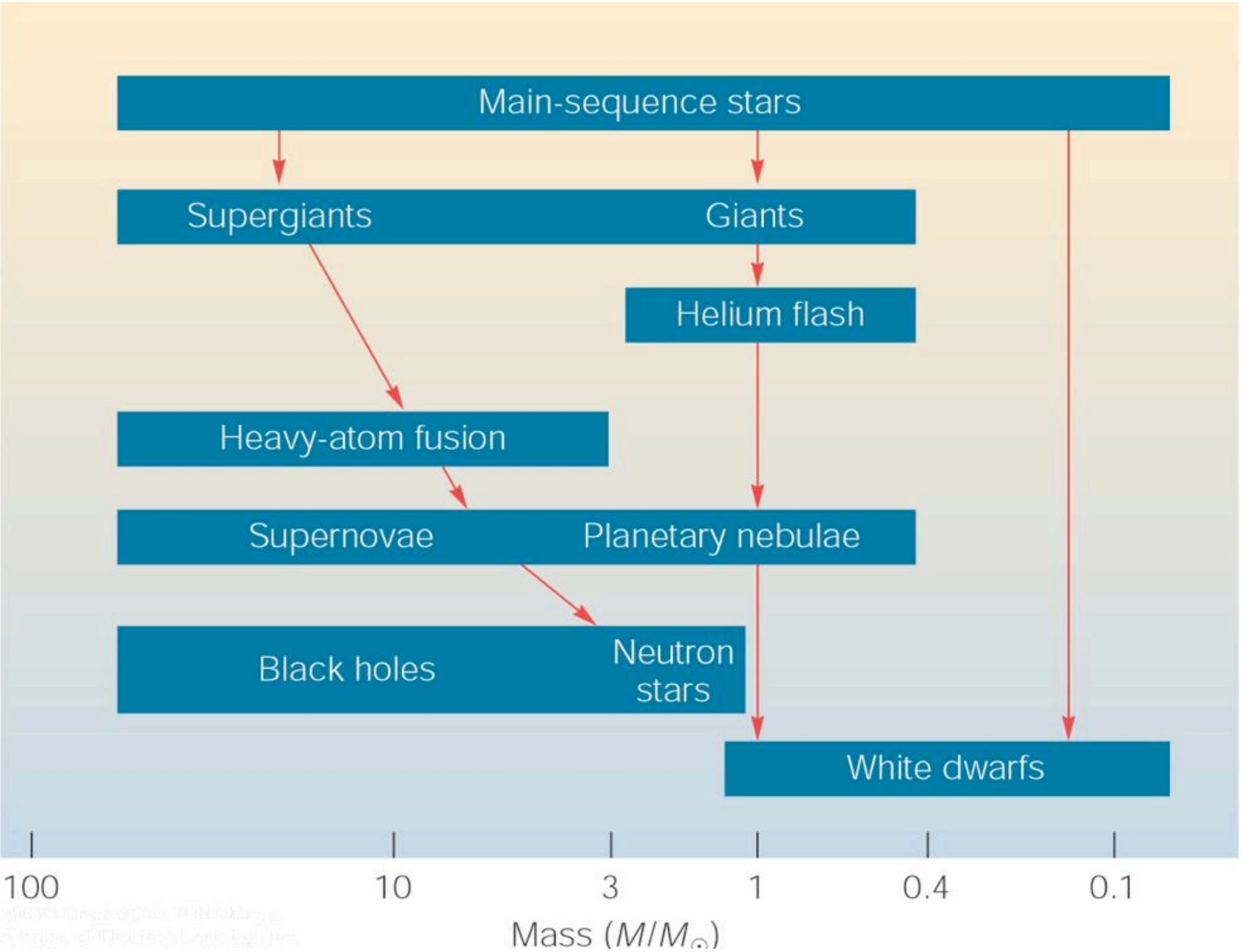
Here are 4 SN remnants observed in the X-ray. From the top left and going clockwise, they are arranged by age, going from 600 to 13000 years old. The oldest remnants are larger because they have heated larger volumes of gasThe first 3 are Type Ia so we see no core left behind. The remnant at the bottom left was a Type II, so we see the neutron star in the centre.



A Brief Summary

Mass ranges are approximate and there is some overlap between categories!

Low Mass Stars	Medium Mass Stars	High Mass Stars
<0.4 solar masses	~few solar masses	>5 solar masses
Can only fuse H	Can fuse H and He	Can fuse heavier elements
Forms red dwarf	Forms red giant	Forms red giant
	Forms PN	No PN
	<1.4 M forms WD	No WD
		SN when Fe in core
Burns slowly all its life and dies in a fizzle	Has some outbursts (like PN) and goes through various guises (giant and WD). Will leave a compact object	Uses its fuel efficiently, until it reaches Fe, evolves quickly and dies as a Type II SN.


Main-sequence stars
Supergiants
Giants
Helium flash
Heavy-atom fusion
Supernovae
Planetary nebulae
Black holes
Neutron stars
White dwarfs
100
10
3
1
0.4
0.1
Mass ($M/M_\odot$)