Advert - Your Universe

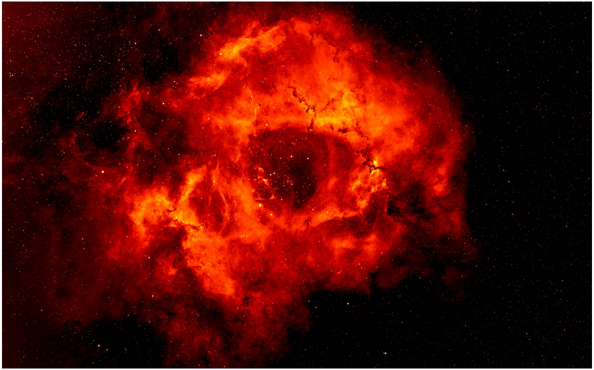
- www.ucl.ac.uk/youruniverse
- An event for the International Year of Astronomy
- Saturday and Sunday - 11am–7pm

Quick summary of last time

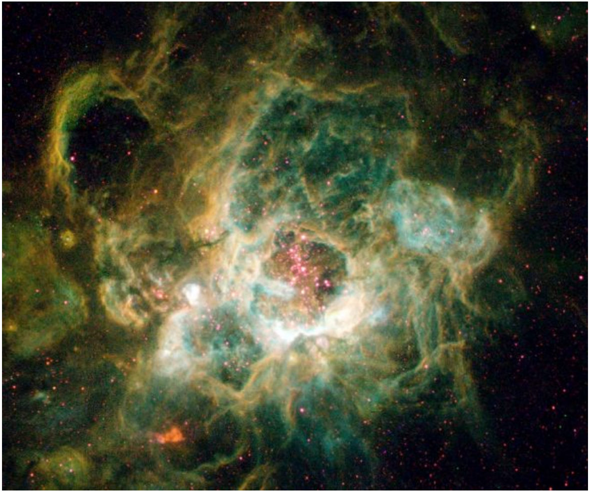
- The Sun, and all stars, shine because of nuclear reactions occurring in their cores.
- Stars form out of large clouds of gas and dust. The largest stars have a mass of about 100 $M_\odot$, and the lightest have a mass of 0.08 $M_\odot$.
- More massive stars are hotter and bluer, and use their nuclear fuel much more quickly so their lives are shorter.
- So, the places where stars have recently formed contain many hot blue stars, which illuminate the gas that the stars have been forming from to form an **H II region**.

Quick summary of last time

- Classic example of H II region is the Orion Nebula. Older H II regions are often 'hollowed out' by the powerful radiation from the hot stars within them – eg the Rosette Nebula:

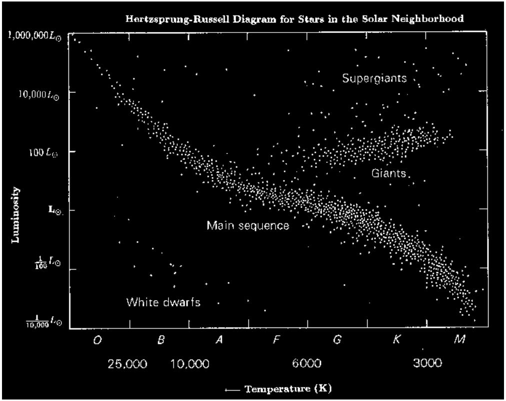


Quick summary of last time



Quick summary of last time

- Once they have begun fusing hydrogen in their cores, stars lie on the **main sequence** in the HR diagram:

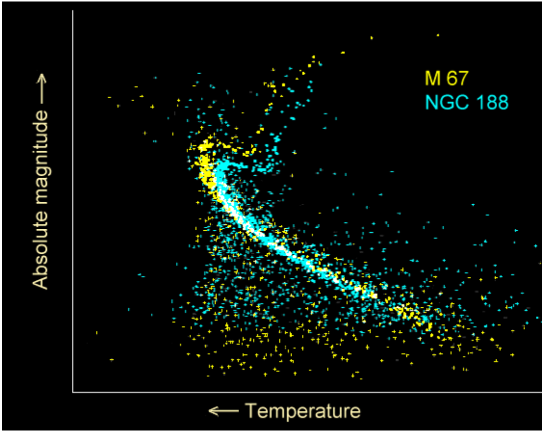


Stellar lifetimes

- 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.

Stellar lifetimes

- Difficult to tell the age of an individual star. But much easier to measure the age of a cluster, by plotting its H-R diagram.

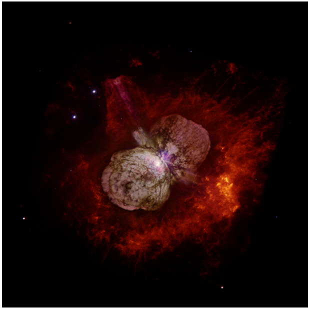


Stellar magnitudes

- In a system ultimately derived from ancient Greek astronomy, the brightness of stars is often described with **magnitudes.**
- The star Vega (which lies almost overhead on summer evenings) has a magnitude of 0.0. Sirius has a magnitude of -1.47. The faintest stars visible to the naked eye are about magnitude 6.
- These magnitudes are **apparent magnitudes**. They allow us to compare the brightnesses of stars as seen from Earth. But this depends very much on distance.

Stellar magnitudes

- The **absolute magnitude** of a star is the apparent magnitude it would have, if it was 10 parsecs away from Earth.
- The absolute magnitude of the Sun is about +4.5. Sirius's is 1.42; Canopus is -5.5. Eta Carinae is -10 or less - emits as much energy in 15 seconds as the Sun does in a year.



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

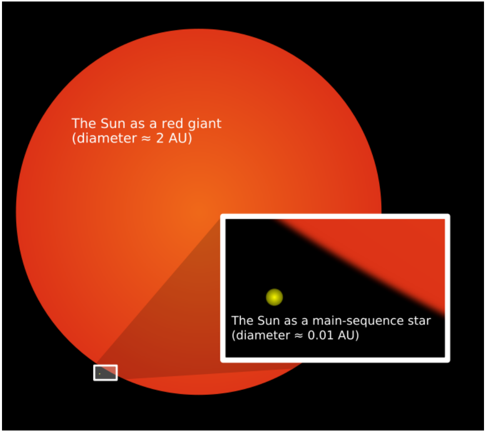
- For stars with less than 0.4 $M_{\odot}$, the temperature does not get hot enough for anything else to happen. The star will end its life as an inert ball of helium, just radiating away its internal heat.
- But the universe is not yet old enough for any stars this light to have burned all their hydrogen.

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!

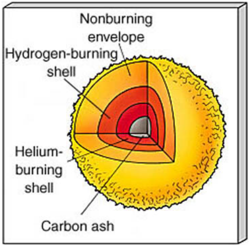


The deaths of stars

- For a black body: $L = 4\pi R^2 \sigma T^4$
- The temperature drops by a factor of $\sim$2, but radius goes up by a factor of $\sim$100.
- So, the luminosity increases by a factor of (100^2 x 0.5^4) = 600

The deaths of stars

- While helium is burning in the core, hydrogen burning continues in a shell around the centre of the star. What happens when helium runs out in the core?
- Again, the core will contract and heat, the star will expand again. An inert carbon-oxygen core is surrounded by a helium-burning shell and a hydrogen-burning shell.

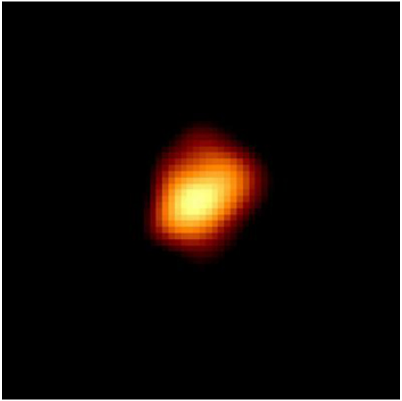


The deaths of stars

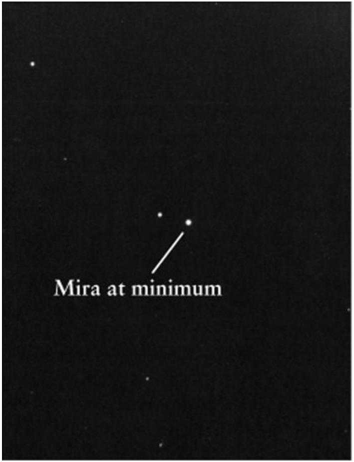
- The rate of helium burning is proportional to T^{40}!!
- In a thin shell, a small variation in the pressure causes a small change in the temperature, which causes a large change in the reaction rate. The burning is extremely unstable, and the star begins to shed its outer layers.

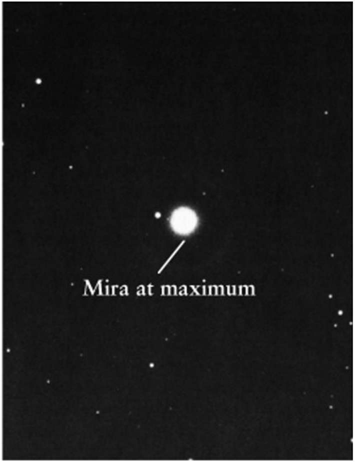
The deaths of stars - Mira

- Unstable helium burning means that evolved stars almost always go through phases where they are pulsating, and therefore varying in brightness. A great example is Mira.

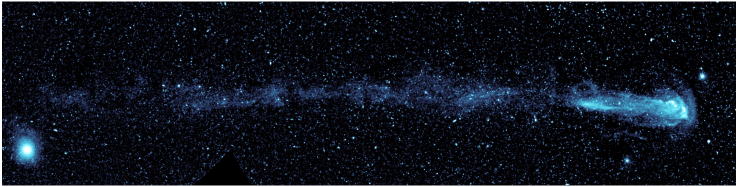


The deaths of stars - Mira



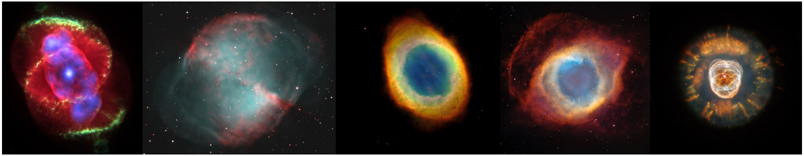


The deaths of stars - Mira



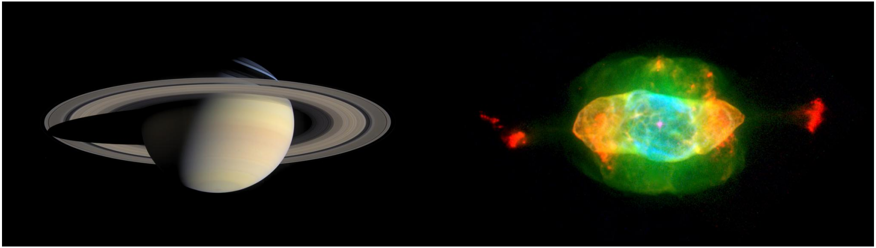
The deaths of stars - planetary nebulae

- 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

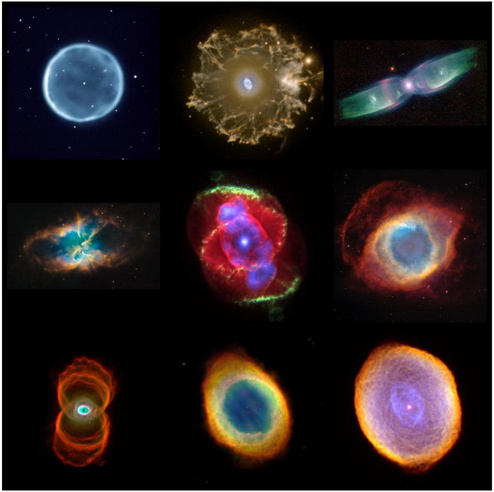


The deaths of stars - planetary nebulae

- The exposed core in a planetary nebula is very hot, but very small and so not very luminous. It is a white dwarf – a compact object roughly the size of the Earth but which may contain a solar mass of material.

The deaths of stars - planetary nebulae

- Why are planetary nebulae so amazingly shaped?



The deaths of stars - massive stars

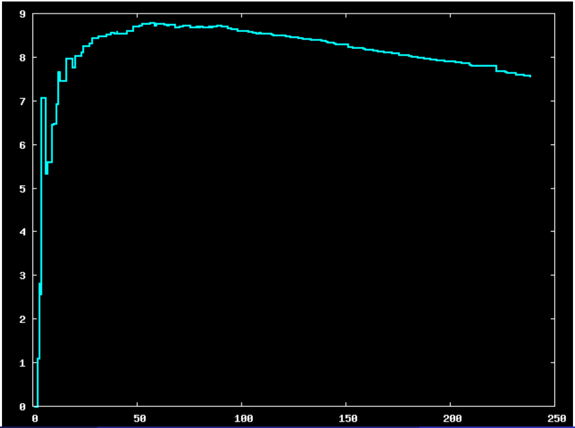
- Stars with masses greater than $\sim 4\,M_\odot$ are heavy enough that nuclear reactions can still proceed in the core despite mass loss. The core will eventually get hot enough for carbon to undergo fusion, forming oxygen, neon, sodium and magnesium.
- Stars with $M \geq \sim 8\,M_\odot$ will fuse 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

- Nuclear fusion releases energy if the product is more tightly bound than the atoms that went into it. This graphs shows how tightly bound atomic nuclei are:

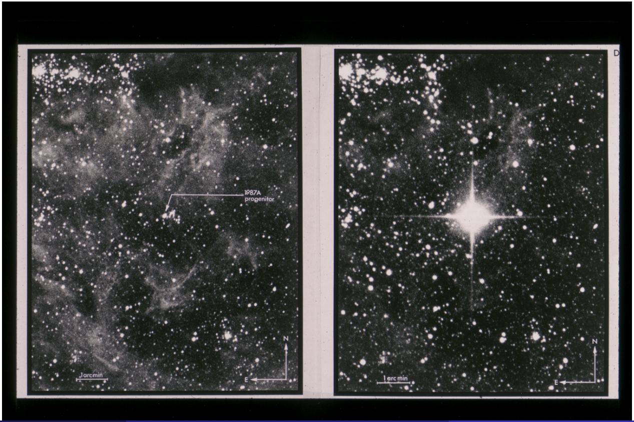


The deaths of stars - massive stars

- 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.



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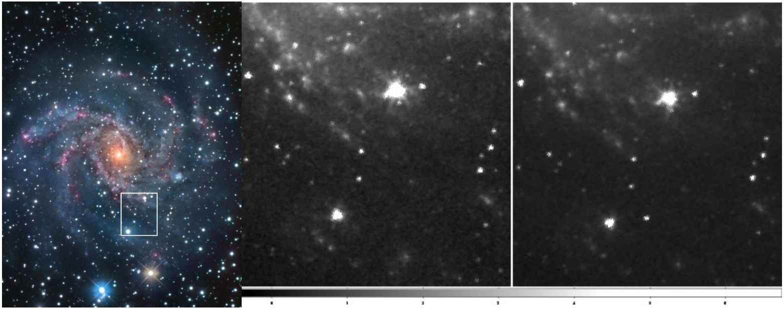
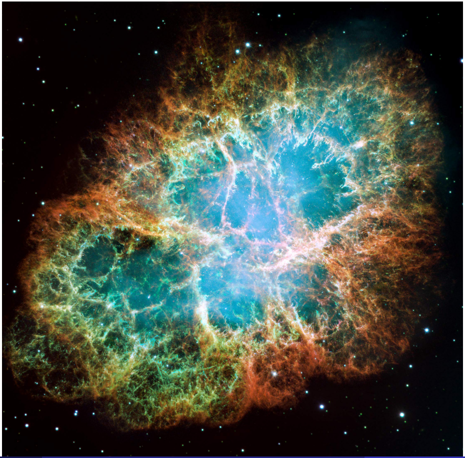


The deaths of stars - supernovae

- Supernovae briefly shine as brightly as a galaxy – and emit as much energy as *hundreds* of galaxies!!
- Most of this energy is carried away in the form of neutrinos. 24 neutrinos from Supernova 1987A were detected on earth – one of the first major successes in neutrino astronomy.
- 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.

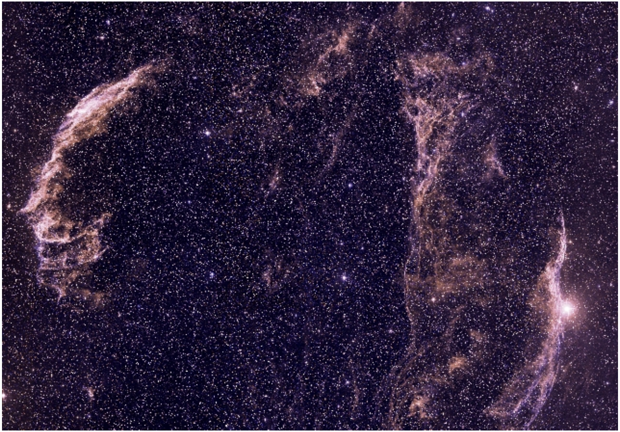
The deaths of stars - supernovae

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



The deaths of stars - supernovae

- Veil nebula - 5 000–8,000 years old



The deaths of stars - supernovae

- Gum nebula - a million years old

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.

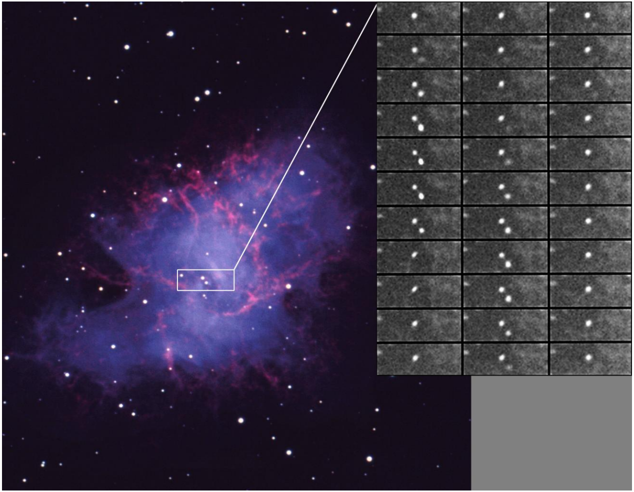
The deaths of stars - neutron stars

- Neutron stars rotate rapidly – the longest period known is only 8.5 seconds, and the shortest is only just over a millisecond.
- They have enormous magnetic fields. They emit a lot of radiation, but much more from their magnetic poles than anywhere else.
- Sometimes, the magnetic pole will point towards the earth once each orbit, and we see a rapidly flickering source. This is called a *pulsar*.

The deaths of stars - neutron stars

- `http://www.amherst.edu/~gsgreenstein/progs/animations/pulsar_beacon/pulsar.gif`

The deaths of stars - neutron stars

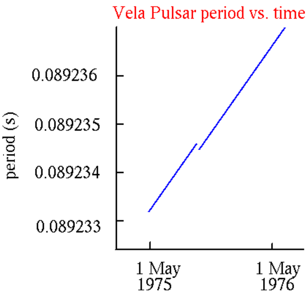


The deaths of stars - neutron stars

- The first pulsar was discovered in 1967, and at first was designated LGM-1.

The deaths of stars - neutron stars

- Crab pulsar pulses 30 times per second
- Slows by 38 nanoseconds/day as it loses energy
- Like all pulsars, it sometimes undergoes *glitches*



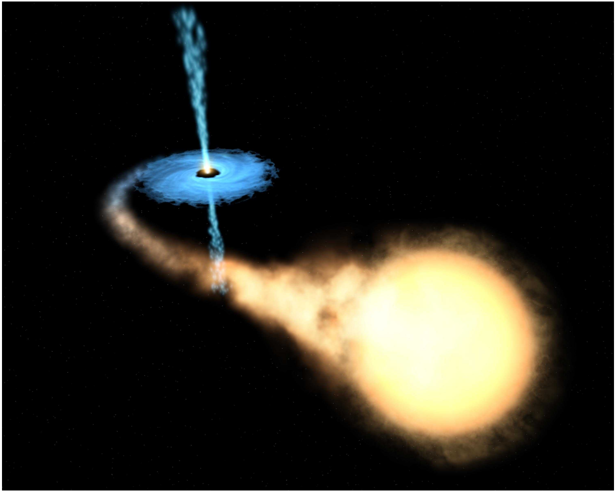
The deaths of stars - black holes

- 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.
- So how would we observe it?

The deaths of stars - black holes

- Could not observe an isolated black hole
- But a binary system containing a black hole might have an *accretion disk*
- These can emit strongly in X-rays.

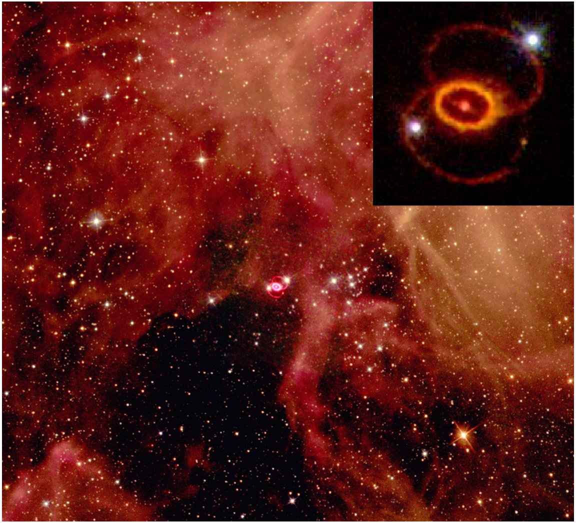
The deaths of stars - black holes



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!

Chemical evolution

- All elements heavier than hydrogen and helium were formed in stars. Younger stars contain more material from previous generations of stars, and have higher *metallicity*.
- Stars can be broadly split into three populations:
  - Population I stars formed recently & contain significant quantities of the heavier elements. The Sun is a Population Istar.
  - Population II stars formed in the earlier universe, and contain only very small amounts of metals.
  - Population III stars are hypothetical, so far, but the very first stars to form in the universe must have contained no metals at all. Population II stars contain some metals, so can't have been the earliest.