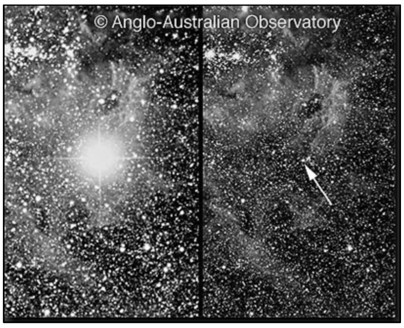
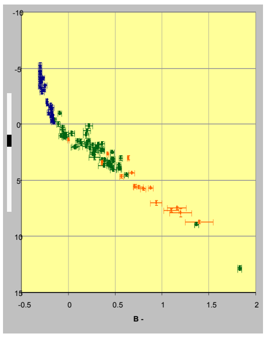
The Deaths of Stars

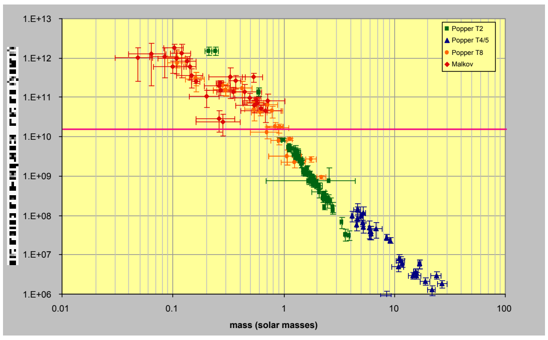
- What happens to stars when the helium runs out?
  - do they simply fade into oblivion?
  - NO!
    - stellar deaths produce some of the most spectacular phenomena in the universe
    - and also play a vital role in enriching with heavy elements the material of which new stars are made



Stellar lifetimes

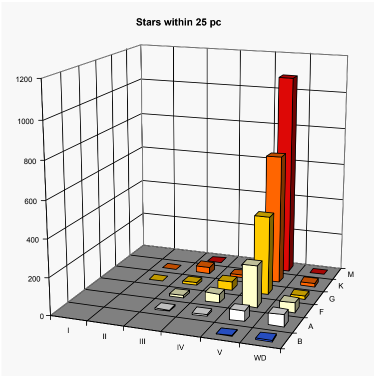
- Our binary star data suggest that the lifetimes of stars with mass < 0.9 Msun are longer than 15 billion years (the age of the universe)
- But massive stars have lifetimes of only a few million years





Stellar statistics

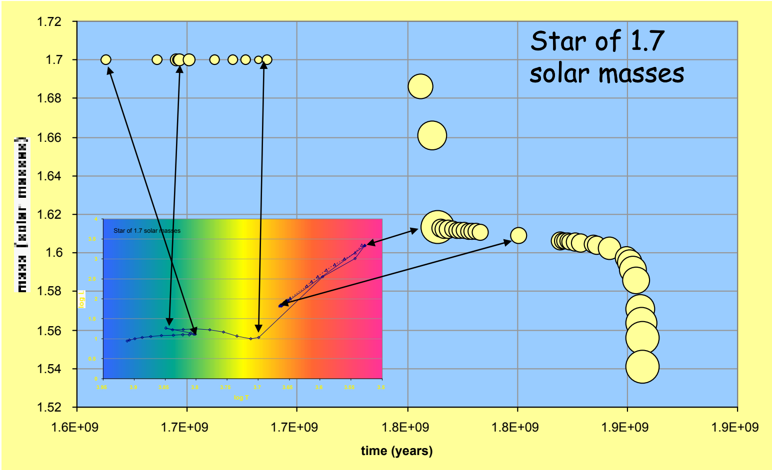
- A census of nearby stars:
  - most stars are low mass red dwarfs
  - a few percent are 1–2 x the Sun's mass
  - very massive stars are very rare (only 3 B and no O class blue stars in the 3800 stars within 75 light years of the Sun)
- ➡ Stellar deaths are rare
  - (but crucial to our existence!)



The deaths of Sun-like stars

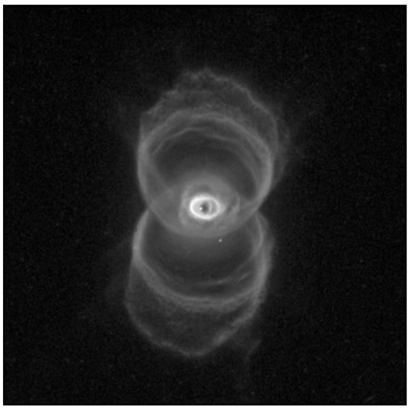
- Giant stars are very unstable
  - especially those which are fusing helium
- Outer layers of star easily lost
  - mass loss seen in spectra of these stars
  - rate increases towards end of helium fusion

Mass loss in Sun-like stars

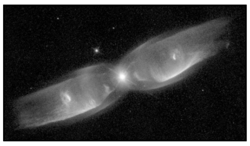


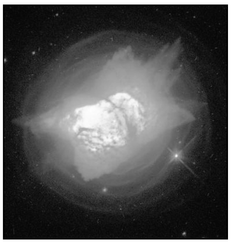
Death of a star

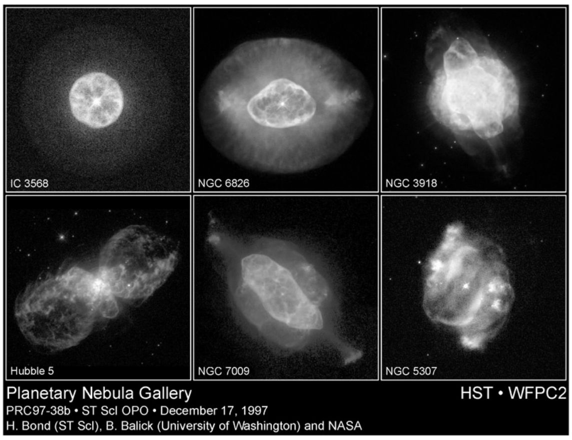
- At end of helium fusion star has lost all its outer layers
  - central, very hot, carbon core surrounded by expelled gas
  - ultraviolet radiation from hot core causes gas to produce emission lines
  - ***planetary nebula***
    - nothing to do with planet, just looks like one!



Planetary nebulae

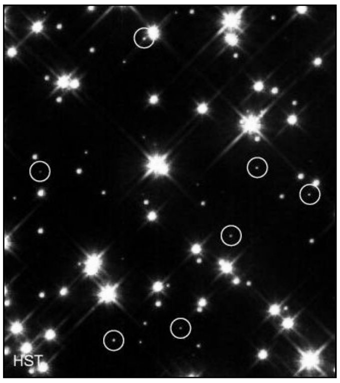






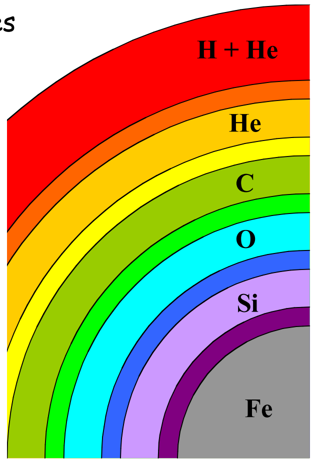
The legacy of Sun-like stars

- Giant stars have convective outer layers
  - elements formed in core are transported to surface
  - thus ejected in planetary nebula
- Planetary nebulae thus enrich the interstellar gas with many elements
  - nitrogen, barium, zirconium, etc.
- Stellar core is eventually revealed as small, hot ***white dwarf*** star



Fusing heavy elements

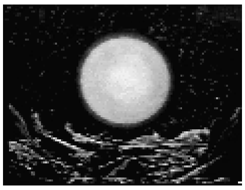
- Massive stars have much hotter cores
  - successfully fuse elements up to iron
- But this is a very temporary respite:
  - for a star of 20 solar masses,
    - hydrogen fusion lasts around 15 million years
    - helium fusion lasts around one million years
    - carbon fusion lasts 300 years
    - oxygen fusion lasts for 7 months
    - silicon fusion lasts for two days and produces an iron core

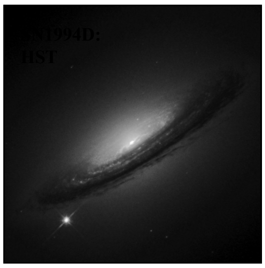


not to scale!

The fate of massive stars

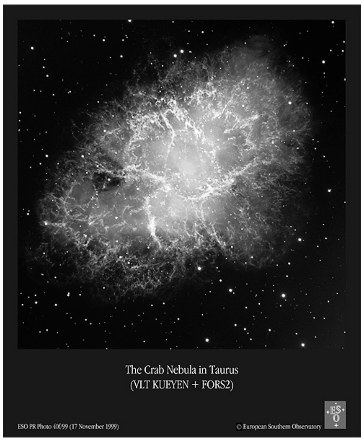
- Fusing iron requires (does not generate) energy
  - iron core cannot support itself against gravity
  - collapses to form ***neutron star***
    - neutron star is about 50% more massive than Sun, but is only 20 km across
    - basically a gigantic atomic nucleus: protons and electrons have combined to form neutrons
    - in extreme cases even this may not be stable, and a **black hole** is formed instead
  - outer layers expelled in massive explosion: a ***supernova***
    - for a few weeks star is nearly as bright as a whole galaxy



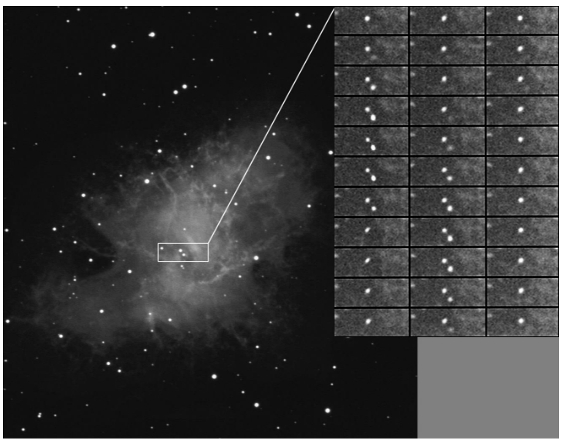


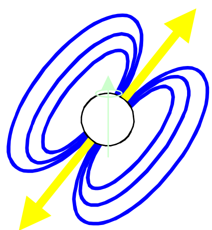
The legacy of massive stars

- Supernova remnants
  - expanding gas cloud, formerly star's outer layers
- Pulsars
  - rapidly rotating neutron stars
    - observed by their "lighthouse beam" of radio emission (sometimes also optical) emitted from magnetic poles of star
- Heavy elements
  - formed in the core of the star as it implodes



The Crab pulsar

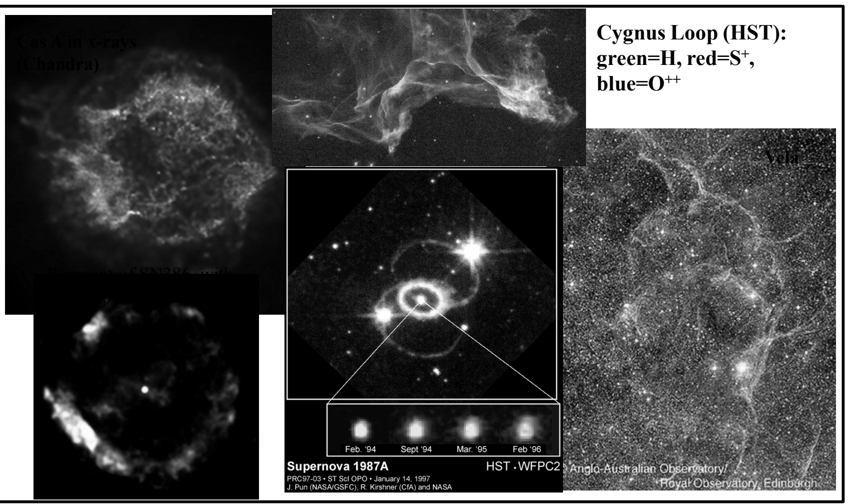




Spin axis and magnetic axis misaligned: see pulse

In Crab see 2 pulses/cycle: angle must be ~90°

Supernova remnants



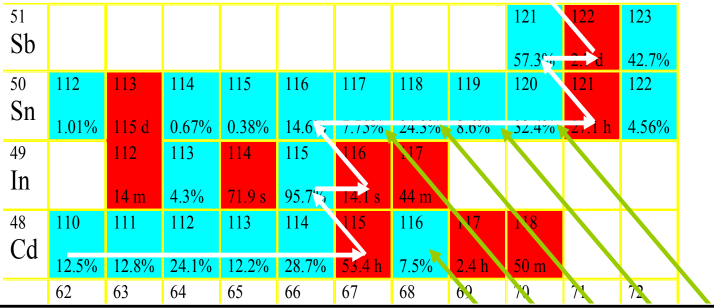
Building the elements

- Routes to building elements:

Start with	Add	In	Making
carbon	protons	H-fusing stars	nitrogen
carbon	helium nuclei (α-process)	He-fusing stars	oxygen-16, neon-20, etc.
carbon-13, neon-22	helium nuclei	He-fusing stars	free neutrons
silicon, sulphur	silicon, sulphur	pre-supernova stars	iron
iron, neon	neutrons, slowly (s-process)	He-fusing stars	most stable isotopes up to Bi
iron	neutrons, rapidly (r-process)	supernovae	neutron-rich isotopes
iron	add photon, lose neutron? (p-pr)	supernovae	rare neutron-poor isotopes

Adding neutrons— why does the speed matter?

- Slow addition of neutrons (s-process) cannot make isotopes that are "shielded" by unstable isotopes (e.g. ^{116}Cd)
- Rapid addition of neutrons (r-process) cannot make those shielded by stable nuclei (e.g. ^{116}Sn)
- Some isotopes (p-process) cannot be made by either method (e.g. ^{112}Sn)



Summary: the abundance of the chemical elements