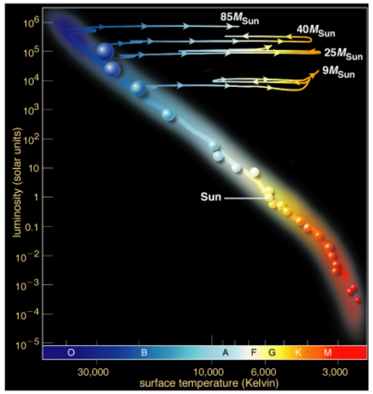
Overview

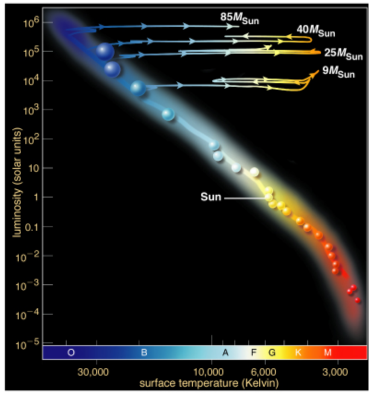
- Evolution of massive stars
- The final moments of a massive star
- Heavy elements and the r-process
- Supernova!
- Supernova remnants

Evolution of massive stars: post-MS



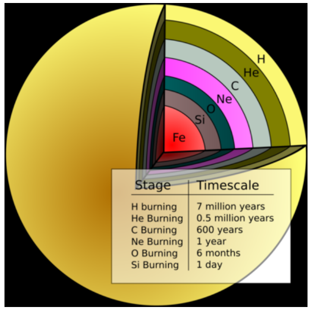
- After core hydrogen runs out, begins moving right on H-R diagram (cooling off and expanding)
- Helium core burning begins
- Later, triple-α process creates C, O
- C,O fusion (with He)
  - Moves up periodic table by 2 each step

Evolution of massive stars



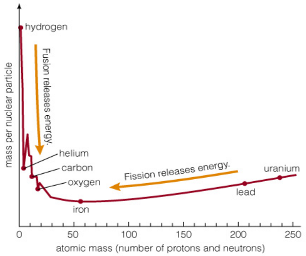
•Massive star: 8 $M_\odot$ or more
•M.S. Evolution: identical to low mass star
•10,000-1,000,000x more luminous than sun: fusion happens much faster
•Only ~10-100x more mass, meaning it can't last as long

Stellar structure and nucleosynthesis in massive stars



Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

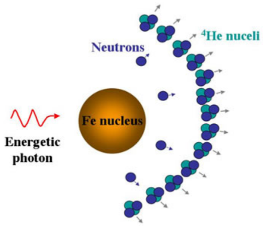
Late stage shell structure of a 25 $M_\odot$ star. Fusion is occurring at the boundaries of each shell. The Iron core is inert. [2]



Fusion can release energy up until iron is formed. Formation of heavier elements uses up more energy than it releases.

The last moments: changing the 'chemistry' of the core

- In the final moments, the core is so hot that there are very high energy photons that can begin to disintegrate the iron nuclei into free protons, neutrons, and helium nuclei. This process is called *photodisintegration.*



Neutronization

- The extremely high density of the core causes electrons to combine with protons, which forms neutrons and neutrinos. This process is sometimes called *neutronization.*

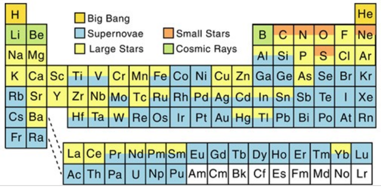
$$e^- + p^+ = n + \nu_e$$

What happens to the pressure in the core when this starts happening?

- Electrons begin to combine with protons, creating neutrons and neutrinos.
  - 0 fingers: I have no idea
  - 1 finger: pressure rises rapidly
  - 2 fingers: pressure falls rapidly
  - 4 fingers: pressure doesn't change
- Photodisintegration uses up energy (climbing backwards up the energy chart)
- Core begins to collapse since there is no pressure supporting it.

Heavy element nucleosynthesis

- Combine photodisintegration with neutronization: lots of free neutrons flying around and get captured by nuclei that didn't get disintegrated. They can also escape from the core and combine with nuclei just outside of it.
- Neutron-rich nuclei can undergo radioactive (beta) decay, producing more neutrinos and allowing the nuclei to settle into stable forms.
- Since there are so many neutrons this process happens rapidly. The elements created this way are called r-process elements ('r' for rapid).



Collapsing core

- The rapid drop in pressure has caused the core to begin rapidly collapsing. Can it stop? If so, how?
  - 0 fingers: not sure
  - 1 finger: it is now getting so hot that thermal pressure can support it again
  - 2 fingers: it can't stop – it just keeps collapsing
  - 4 fingers: degeneracy pressure from the neutrons

Neutrino party

- Sudden generation of many neutrinos in the core.
- Since the core is now mostly neutrons and very, very dense, the neutrinos interact frequently, so they do a random walk in the core.
- The neutron core boils, bringing heat and neutrinos to its surface.
- Core is very compact – takes only seconds for this to happen
- Gives rise to a sudden burst of neutrinos coming out of the core.

Stopping the collapse

- Photodisentegration is absorbing energy, and neutrinos are carrying energy out of the nucleus, so it can't get hot.
- Neutron degeneracy pressure becomes important before complete collapse.
- *** If it is massive enough (*core* greater than about 3 solar masses) neutron degeneracy pressure is insufficient and collapse will continue to a black hole.

SN 1987a

- Nearest observed supernova in modern astronomy: 168,000 ly away in the Large Magellanic Cloud (LMC)
- 'Occurred' in 1987 – the explosion happened 168,000 years ago, the light reached us in 1987

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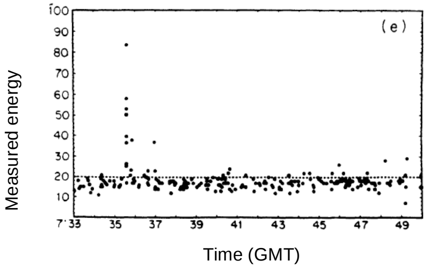
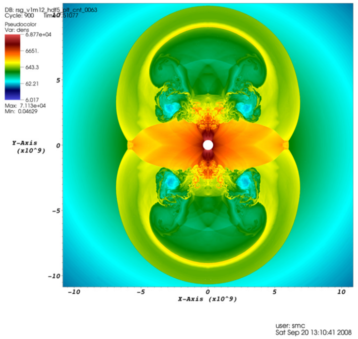
SN 1987a neutrinos



- Total energy from neutrinos measured at Kamiokande-II, Feb 23 1987.
- Very large peak at about 7:35:25 GMT due to neutrinos from SN 1987a. This was also measured at two other neutrino observatories.
- Neutrinos arrived before the light! Not because they moved faster, simply because the neutrinos escaped the supernova before the light did (for the same reason neutrinos escape the sun's core faster than light does)
- Total energy in the neutrinos: 10^{53} erg (10^{20}x what the Sun puts out in light in one second). This represents about 99% of the energy of the explosion.

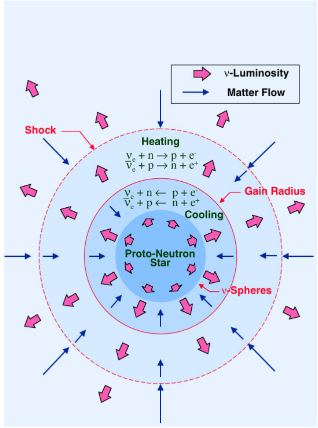
Jet formation

- Star and core is rotating. As the core shrinks, its rotation gets faster.
- Rapid rotation with infalling material make the poles a natural outlet for pressure.
- The rotation also generates strong magnetic fields.
- The combination of magnetic field and opening at the poles causes a jet to form, 'squirting' out material at a high speed.
- In some of the most massive stars, this may be the cause of gamma ray bursts (GRBs) [discussed later this semester]

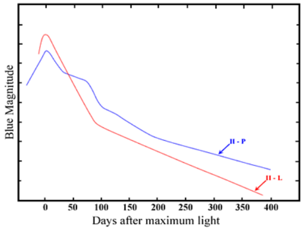


Core collapse and rebound

- Core rapidly collapses until neutron degeneracy pressure suddenly kicks in
- Material from outside core is falling inward; it hasn't 'gotten the message' that the core is supported.
- Material bounces off of core.
- Standing shock wave develops as material falls inward so quickly that shock can't escape.
- Neutrinos are somehow involved in heating the material and adding to the shock. This is poorly understood and an active area of research.
- Eventually shock overcomes material falling inward: explosion – Supernova!



The first year



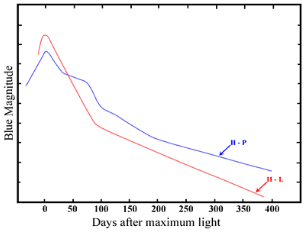
- Type II supernova, characterized by hydrogen absorption lines in the spectrum.
- In the first few days, the remnant is getting bigger and not cooling much, so it starts to get very bright.
- Eventually it gets big enough that in begins to cool. The supernova reaches a peak brightness then begins to dim.
- Most supernova (those with a larger hydrogen envelope) have a plateau in their light curve at about the two month mark as ionized hydrogen begins to recombine, releasing more light. These are called Type II-P. The few that don't have this feature are called Type II-L
- After about 75 days, the dropoff in light slows down.

Some heavy metals on Earth

Isotope	Half-life	Abundance (Earth)	Generation
Iron-54	Stable	6% (of Iron)	alpha process fusion
Iron-56	Stable	92% (of Iron)	decay of cobalt-56
Cobalt-56	77 days	0% (of Cobolt)	r-process, decay of Nickel-56
Nickel-56	6 days	0% (of Nickel)	alpha process, r-process

Large amounts of Nickel-56 is created during the final moments of the supernova. This quickly decays into Cobalt-56.

The radioactive decay of Cobalt-56 is responsible for most of the luminosity of the supernova after about 75 days.



Supernova Remnants

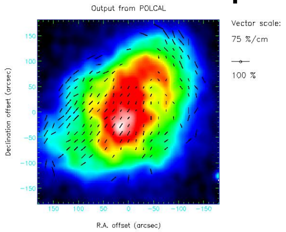


Image of the Crab nebula showing polarization (arrows). Polarization is indicitive of relatively strong magnetic fields.

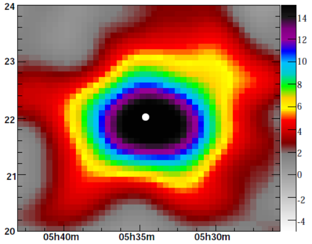
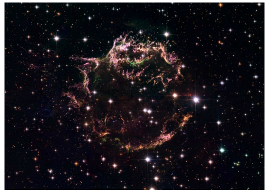


Image of the region near the Crab nebula in gamma rays (low resolution so its very smeared out). Crab nebula is white dot in center.

Supernova remnants are a primary source of *cosmic rays* due to the magnetic fields and strong shock.

Supernova remnants



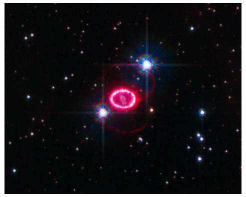
Cassiopeia A (SN 1667?)

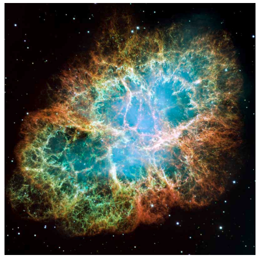
Supernova wasn't observed at the time, but we can date the remnant to that year.

SN 1987a

Note faint outer rings are evidence of earlier mass loss events, indicator of binary system.

Bright inner ring is supernova ejecta slamming into material ejected in earlier outburst.





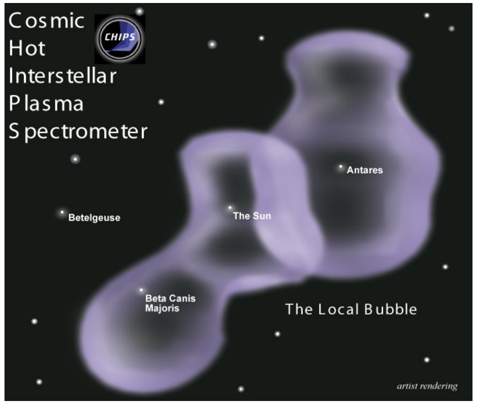
Crab Nebula (SN 1054)

Supernova recorded by Arab, Chinese, and Japanese astronomers. Nebula first observed in 1731 by John Bevis, and independantly again in 1758 by Charles Messier.

Supernova remnants & ejecta

- The shock from the supernova is traveling outward at about 10% the speed of light.
- The ejecta carrys the newly synthesized elements with it into the interstellar medium, ready to become the next generation of stars.
- When the shock encounters a stable gas cloud it mixes metals into the gas cloud, and may cause the cloud to compress enough to start collapsing – this begets a new generation of star formation.
- When many supernova explode near each other, can blast holes in galaxies causing galactic winds and enriching the intergalactic medium with heavy elements.

The local bubble



Low density region of the galaxy in the vicinity of the sun, caused by several supernova from a nearby cluster

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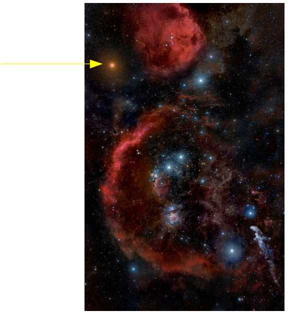
Compact remnants (what happened to the core?)

Mass of progenitor star (solar masses)	Core remnant
8 - 25	Neutron star (core is not massive enough for black hole)
25 - 140	Black hole or neutron star, dependent upon original metal content
140-250	None – it blows itself apart!
250+	Massive black hole

Betelgeuse



- Betelgeuse is a red supergiant in the constellation Orion.
- Mass is between about 8 and 20 $M_\odot$.
- It was ejected from the cluster of stars in which it was born. From that cluster, we can determine its age to be about 7 million years.
- Distance: about 650 ly.

Takeaway points

- Stars of 8-25 $M_\odot$ generate alpha-process elements in their later stages. Each stage is successively shorter.
- In the final moments, the core collapses and protons are converted to neutrons.
- Nearly the entire star falls inward and bounces off the core. This process causes an explosion (supernova).
- The explosion releases heavy elements into the galaxy. The shock wave can cause new generations of stars to form.
- The core of massive stars may be left behind as a neutron star, or may collapse into a black hole.