Lecture 10: The death of stars

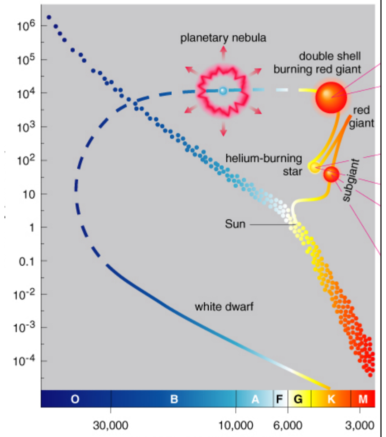
- The death of low mass stars and formation of white dwarfs
- The late evolution of massive stars
- Supernovae
- Summary of evolutionary pathways

The death of low mass stars

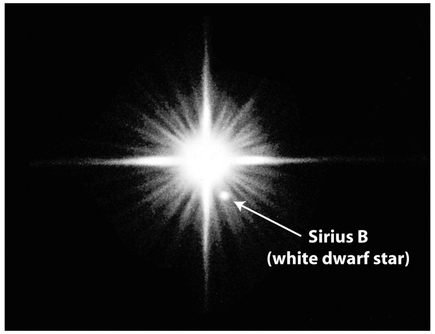
•Ejection of the stellar atmosphere leaves the compact carbon-oxygen core.

•The drastic shrinkage of the star leads to a dramatic drop in luminosity.

•What remains is a white dwarf star, in the lower left portion of the H-R diagram.



The burned-out core of a low-mass star cools and contracts until it becomes a white dwarf

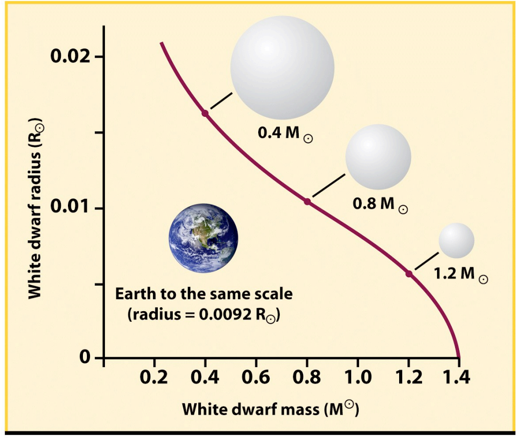


- No further nuclear reactions take place within the exposed core
- Instead, it becomes a degenerate, dense sphere about the size of the Earth and is called a white dwarf
- It glows from thermal radiation; as the sphere cools, it becomes dimmer

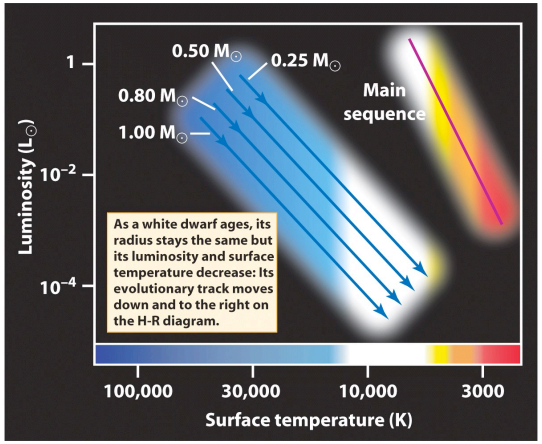
White dwarf stars

- The carbon nuclei and electrons in the core of a white dwarf are packed together very tightly: about 1 solar mass in the volume of the Earth.
- One teaspoon of white dwarf matter has a mass of about 5 tons. Electron degeneracy pressure prevents the white dwarf from collapsing under its own weight.
- Electron degeneracy pressure occurs because, quantum mechanically, electrons do not like to be too close to each other (being fermions).
- Nonetheless, if the mass exceeds 1.4 solar masses, gravity will overcome electron degeneracy pressure and the core will contract, or even collapse catastrophically resulting in a supernova explosion.

More massive white dwarfs are *smaller*



The evolution of white dwarfs



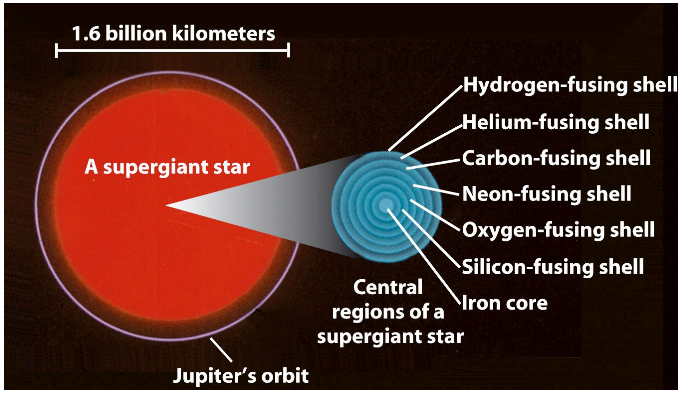
The late evolution of high mass stars

- In stars with $M > 8M_\odot$, electron degeneracy cannot stop the C-O core from contracting further and heating up.
- This leads to further stages of nuclear burning, including the fusion of carbon, neon, oxygen and silicon.
- These subsequent stages start in the core, and later switch to shells, just like H and He burning.
- Each stage proceeds more rapidly than the last, due to faster reaction rates, and diminishing energy returns.

table 22-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage	Core temperature (K)	Core density (kg/m^3)	Duration of stage
Hydrogen fusion	4×10^7	5×10^3	7×10^6 years
Helium fusion	2×10^8	7×10^5	7×10^5 years
Carbon fusion	6×10^8	2×10^8	600 years
Neon fusion	1.2×10^9	4×10^9	1 year
Oxygen fusion	1.5×10^9	10^{10}	6 months
Silicon fusion	2.7×10^9	3×10^{10}	1 day
Core collapse	5.4×10^9	3×10^{12}	¼ second
Core bounce	2.3×10^{10}	4×10^{15}	milliseconds
Explosive (supernova)	about 10^9	varies	10 seconds

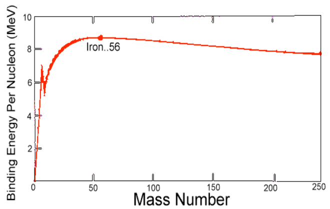
Internal shell structure of a late-stage massive star

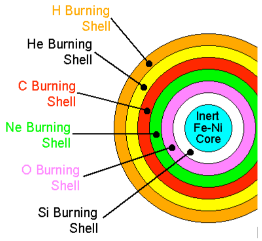


In the final stages of its life, a high-mass star has an iron-rich core surrounded by concentric nuclear burning shells.

The end of nuclear fusion

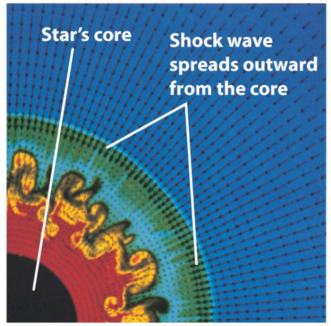
- The sequence of thermonuclear reactions stops at iron, because the iron nucleus has the largest binding energy per nucleon of any element
- Hence the formation of elements heavier than iron requires an input of energy, rather than being exothermic
- Therefore, once a substantial iron core has been formed, there is no energy source left to support it against the pull of its own gravity
- This leads to core collapse and a supernova explosion





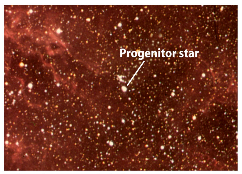
Supernovae

- Core collapse releases large amounts of gravitational energy, $E \sim GM^2/R_{final}$
- This powers many endothermic nuclear reactions and generates a huge flux of neutrinos
- When the core reaches nuclear densities, the nucleons become degenerate, and neutrinos are also unable to escape easily
- This generates a huge increase in pressure, and the core collapse is stopped abruptly in a "bounce"
- This ejects the outer layers of the star at very high velocity, causing a powerful explosion

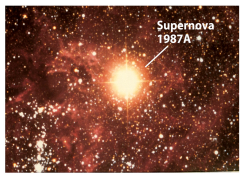


Computer simulation showing structure 10 ms after core bounce

An example - SN1987A



Before the star exploded



After the star exploded

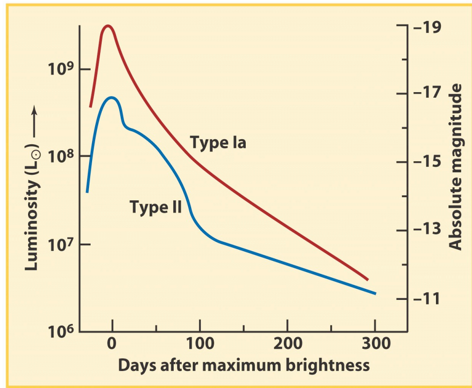
- Supernova 1987A in the Large Magellanic Cloud is the closest supernova seen for over 300 years.
- Its peak luminosity of ~10^8 $L_\odot$ was rather low by typical SN standards.

Supernovae of type Ia and II

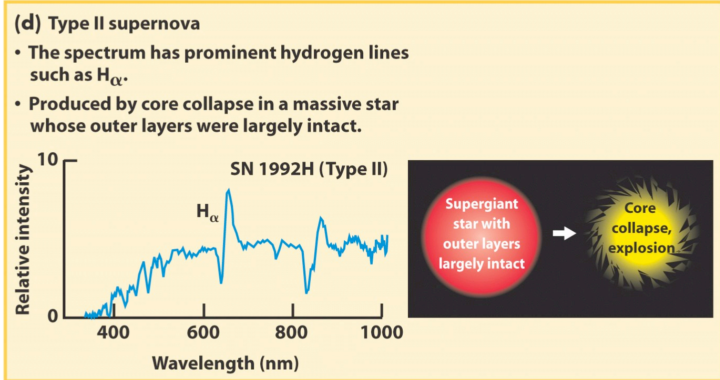
There are two main types of supernovae, which have distinct lightcurves and spectra.

Supernovae resulting from the explosion of massive stars at the end of their lives are normally of type II. These show H lines in their spectra, and have rather variable lightcurves.

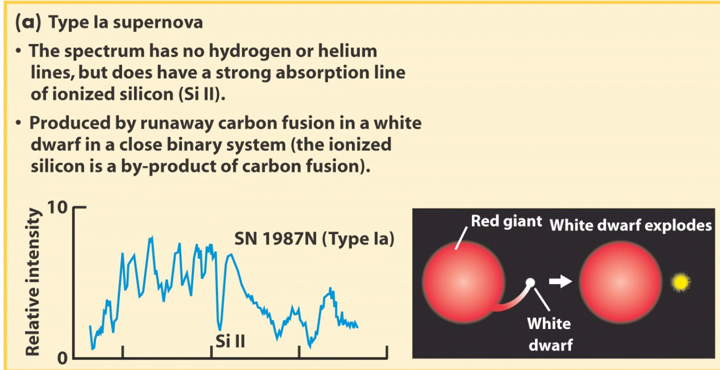
Type Ia SNe are much more uniform, and have no H lines.



Type II supernovae are created by the deaths of massive stars



Type Ia supernovae are produced by accreting white dwarfs in close binaries



Supernova remnants

The expanding shock wave generated by a supernova expands out into the surrounding interstellar medium, generating a supernova remnant which may be visible for many thousands of years.

Summary - pathways of stellar evolution