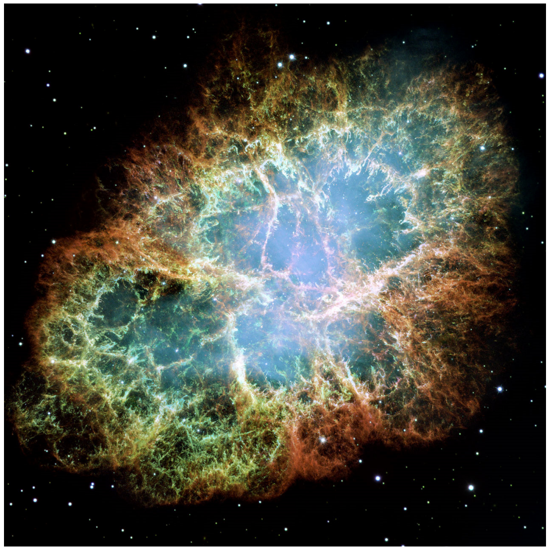
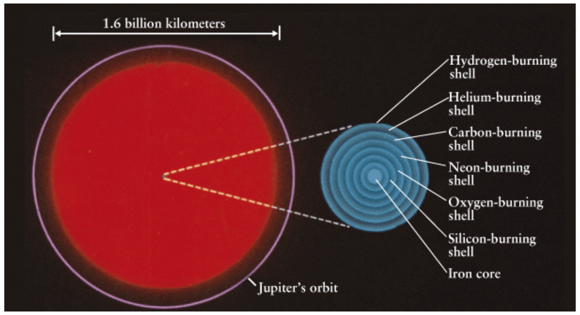
Explosive Deaths of Stars
Sections 20-5 to 20-10



Evolution of high mass stars

- For stars with initial masses > 7 M⊙, the fusion process goes beyond C and O.
- Possible because central temperatures high enough for C, O fusion. Core hot enough so still an ideal gas, not degenerate. Fusion starts without a flash.



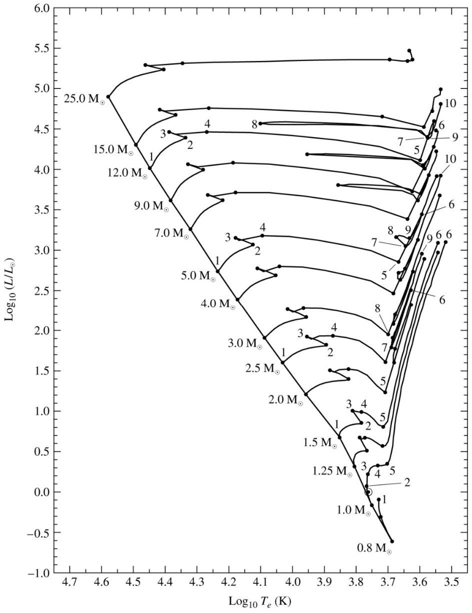
Onion shell buildup

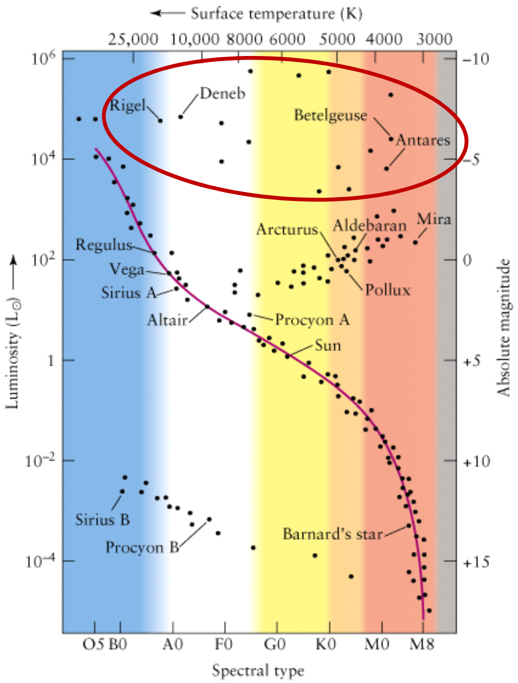
1. Pick up from stage where inert C-O core contracts and heats up, H & He shell burning.
2. C-O core contracts until T~ 6×10^8 K: igniting C. Fusion of ^{12}C with ^{12}C or ^{4}He produces ^{16}O, ^{20}Ne, ^{24}Mg.
3. Inert O-Ne-Mg core contracts and heats up, H & He & C shell burning. (For M~7(?) – 8(?) M⊙, fusion ends with O, Ne, Mg and core *does* become degenerate. Explains rare "O-Ne-Mg White Dwarfs").
4. If M>~ 8 M⊙, core contracts until core T ~ 10^9 K, fusion starts again, mainly $^{20}Ne \rightarrow {}^{24}Mg$.
5. When exhausted, core shrinks, shell of Ne fusion established. When core T~1.5×10^9 K, fusion starts, mainly $^{16}O \rightarrow {}^{28}Si$, ^{32}S.
6. Then core contracts, shell of O fusion established. When core T~2.7×10^9 K, ^{28}Si, ^{32}S fuse to mainly ^{56}Fe, ^{54}Fe, ^{56}Ni.

Stars evolve at nearly constant *L* in H-R diagram.

Evolution generally to redder color and larger radii.

Details are complex and not important: back and forth motion associated with establishment of new core fusion sources, and tracks are affected by rotation of star, mass loss via winds, degree of convection, etc.





A massive red supergiant.

The core has an onion-layer structure, with shells of greater radius fusing heavier elements

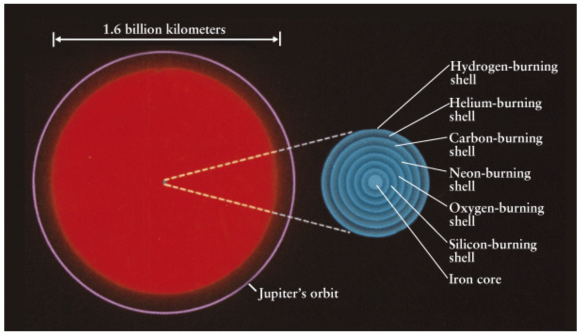
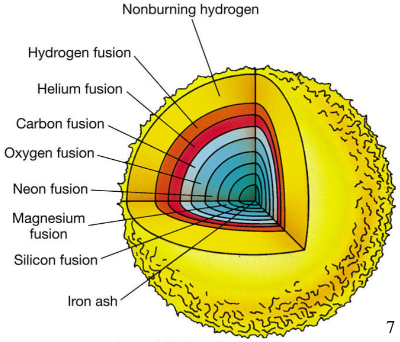


table 22-1 Evolutionary Stages of a 25-$M_\odot$ Star

Stage (core)	Core temperature (K)	Core density (kg/m³)	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

Where does it stop?

- A very high mass star can process all the way to iron (^{56}Fe) by normal fusion.
- Why? Fusion of Fe (and heavier nuclei) absorbs energy instead of liberating it. Fe core contracts, heats up: a catastrophic collapse is unavoidable.



Core collapse

- *Photodisintegration*: For massive stars (>~ 8 M⊙), when the core temp reaches 5 x 10^9 K, γ-rays disintegrate Fe nuclei (1/10 s) => He => p, n
- *Neutronization*: In another 1/10 s, core becomes so dense that electrons and protons are forced together to create neutrons via

$$e^- + p^+ \rightarrow n + \nu$$

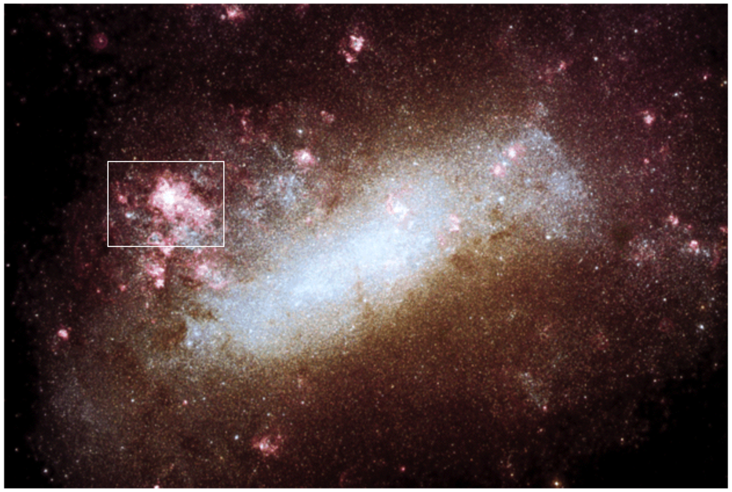
- Energetic neutrinos mostly escape, robbing the core of more energy so it collapses faster.
- After 0.25s, core reaches nuclear density ~10^{17} kg/m^3 (from ~10^{10} kg/m^3). The neutrons resist further compression, i.e. neutron degeneracy pressure stops collapse and core becomes extremely rigid.
- When collapse stops ⇒ overshooting causes a *core bounce* (launching a powerful shock wave outwards).

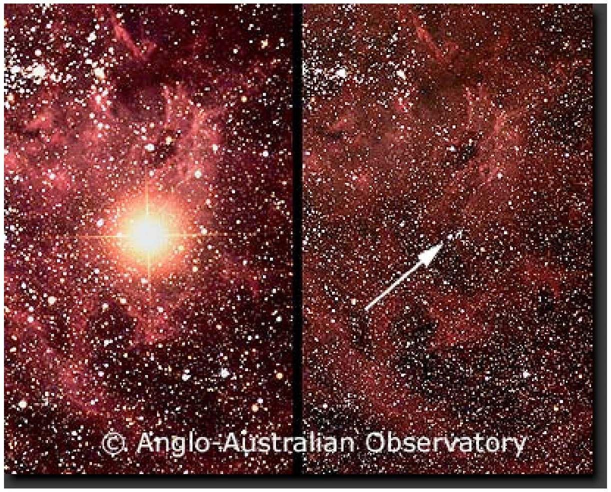
At the start of the iron core collapse, the core is ~6000 km. A second later it is ~50 km!

A Core-collapse Supernova

- Outside the core, material is falling inward at about 0.15c. This is because the core is losing energy, catastrophically collapsing, and thus providing no support.
- As this material crashes toward the core, the shock wave blasts it outwards.
- In a few hours the shock gets to the outer layers and breaks out from the surface at about 0.1c. Fast ejection of the entire envelope, blast of radiation. At peak brightness, $L \sim 10^9 L_\odot$.
- This is a core-collapse or Type II (why? later…) *supernova.*

Thus far, theory. In 1987 light from a supernova in Large Magellanic Cloud (dwarf galaxy near Milky Way) reached us, providing a good test.

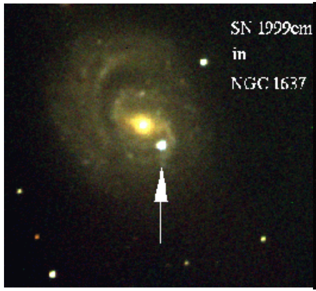




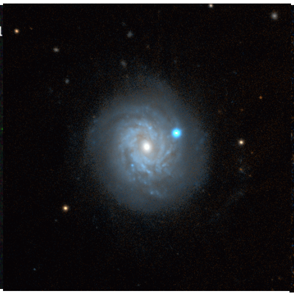
Neutrinos and supernovae

- About 98% of the energy of a supernova comes out in the form of neutrinos, which are formed in the neutronization process.
- From SN1987A we detected burst of neutrinos at 2 different neutrino detectors. They arrived 3 hours before the visible light.
- Why before? Light emitted only when shockwave gets out of core, reaches surface layers of star.

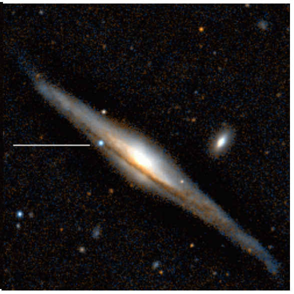
Supernovae can rival brightness of their host galaxy, and we can see them across the Universe.



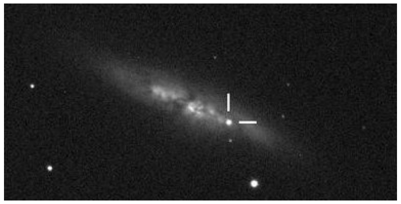
NGC1637, 1999
(9Mpc)



NGC3982, 1998
(23Mpc)

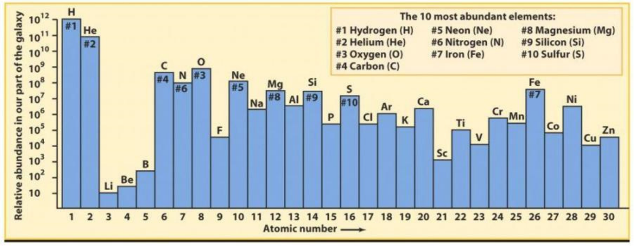


NGC5965, 2001
(50Mpc)



M82, 2014 (6Mpc)

Remaining Nucleosynthesis



- Some elements not yet mentioned, such as Al, P, made by rare fusion reactions in normal stellar evolution.

- Elements beyond iron in the periodic table created during late evolution of massive stars (lead, gold, copper, silver, etc.) and SN explosion itself (thorium, uranium, plutonium, etc.), by "neutron capture": some reactions create free neutrons – many more created in supernova. These can be absorbed by other nuclei. If nucleus now unstable, n decays into p => new element.

- This enriched material is eventually available for the formation of the next generation of stars and planets.

Types of supernovae

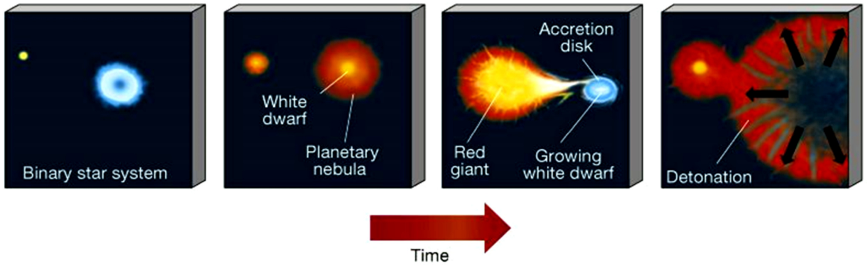
- Supernova classified observationally by spectra of debris. Then must relate to progenitor properties.

- "Type II" supernovae show hydrogen emission lines in their spectra.

- Why? These highly massive stars still have H in their atmospheres while exploding due to core collapse.

- Type I supernovae show no hydrogen lines. They divide into Type Ia, Ib and Ic. Last two are special cases of core collapse in massive star. Type Ia is quite different.

Type Ia or Carbon-detonation supernovae



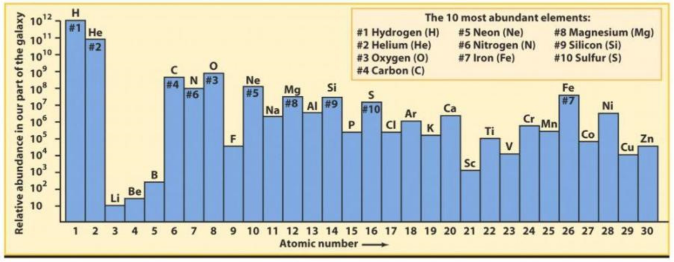
- Consider white dwarf in close binary system.

- Mass transfer pushes white dwarf toward "Chandrasekhar limit" of 1.4 $M_{\odot}$. Here gravity overwhelms degeneracy pressure, star contracts and gets very hot.

- Carbon suddenly ignites in core, because it is degenerate the fusion rate increases rapidly: the star blows up.

Thermonuclear runaway

Iron in universe generally comes from this runaway fusion in WDs

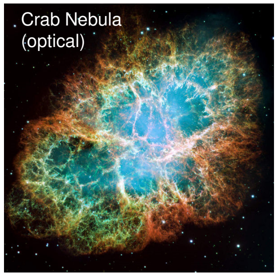


- Type Ia SN have critical importance in understanding the Universe as a whole: they are *standard candles.*
- No matter where in the Universe they happen, they are physically similar: WD with about 1.4 $M_\odot$ (the Chandrasekhar limit), so they produce similar explosions.

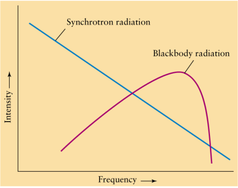
Why is this useful? Would Type II's be as good as standard candles?

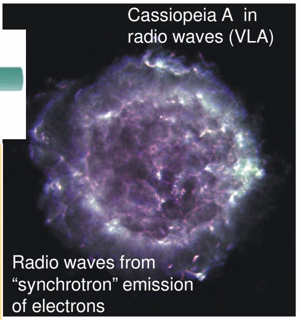
Supernova remnants (SNRs)

- The extreme violence of a supernova blasts the outer layers of the star into the ISM.
- This enriches the ISM with heavy elements and accelerates atomic nuclei and electrons to speeds near *c*, travel across the Galaxy and are called *cosmic rays* when they hit the Earth.
- In addition, the collision between the shock and the ISM excites the gas and makes it glow: supernova remnants



Crab Nebula (optical)





Cassiopeia A in radio waves (VLA)

Radio waves from “synchrotron” emission of electrons

Summary of star deaths