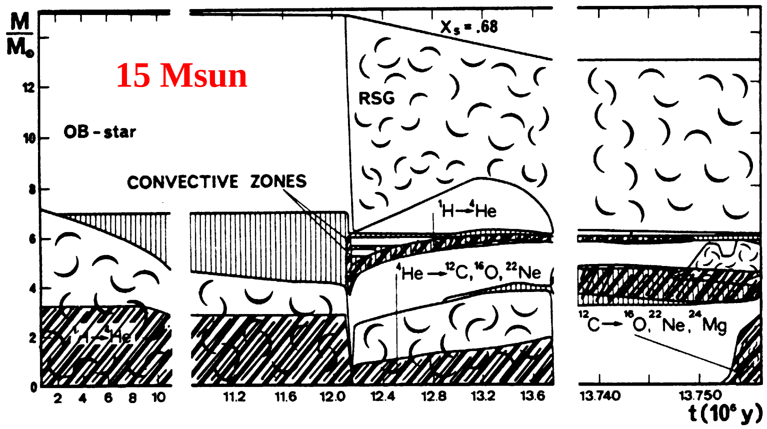
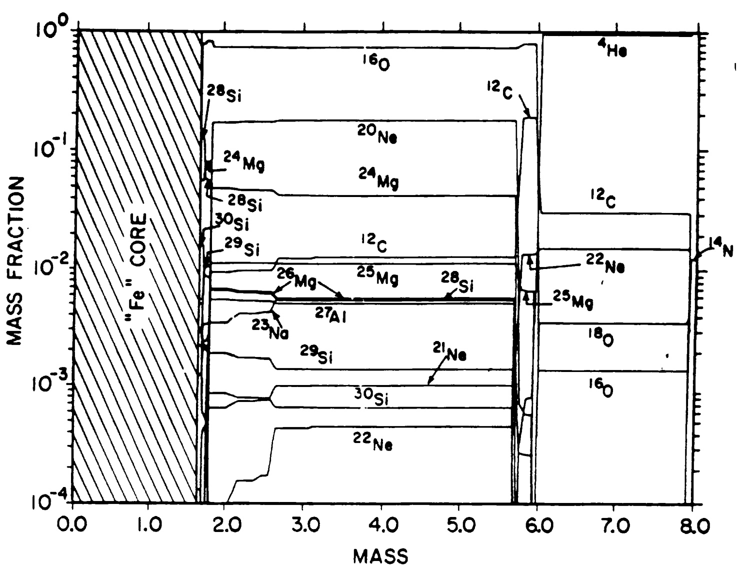
Evolution of Massive Stars



Maeder (1987)

Helium Core (8 Msun)



Itoh and Nomoto (1987)

6.3 EVOLUTION OF MASSIVE STARS ($M \gtrsim 13\,M_\odot$)

(CO: 13.3)

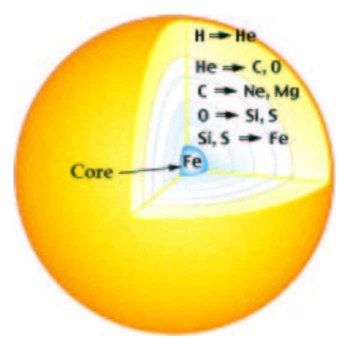
- massive stars continue to burn nuclear fuel beyond hydrogen and helium burning and ultimately form an iron core
- alternation of nuclear burning and contraction phases
  - ▷ carbon burning ($T \sim 6 \times 10^8$ K)

$$
\begin{aligned}
{}^{12}C + {}^{12}C &\rightarrow {}^{20}Ne + {}^{4}He \\
&\rightarrow {}^{23}Na + {}^{1}H \\
&\rightarrow {}^{23}Mg + n
\end{aligned}
$$

  - ▷ oxygen burning ($T \sim 10^9$ K)

$$
\begin{aligned}
{}^{16}O + {}^{16}O &\rightarrow {}^{28}Si + {}^{4}He \\
&\rightarrow {}^{31}P + {}^{1}H \\
&\rightarrow {}^{31}S + n \\
&\rightarrow {}^{30}S + 2\,{}^{1}H \\
&\rightarrow {}^{24}Mg + {}^{4}He + {}^{4}He
\end{aligned}
$$

  - ▷ silicon burning: photodisintegration of complex nuclei, hundreds of reactions → iron

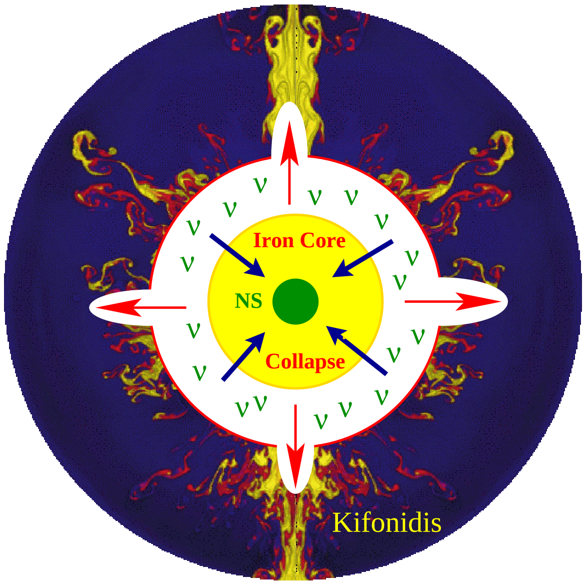


- ▷ form iron core
- ▷ iron is the most tightly bound nucleus → no further energy from nuclear fusion
- ▷ iron core surrounded by onion-like shell structure

6.4.1 EXPLOSION MECHANISMS (ZG: 18-5B/C/D)

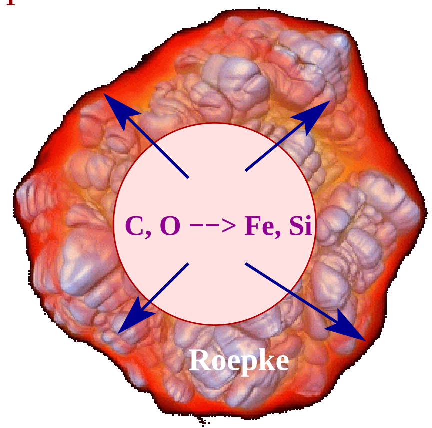
- two main, completely different mechanisms

Core-Collapse Supernovae



- triggered after the exhaustion of nuclear fuel in the core of a massive star, if the iron core mass > Chandrasekhar mass
- energy source is gravitational energy from the collapsing core ($\sim 10\,\%$ of neutron star rest mass $\sim 3 \times 10^{46}$ J)
- most of the energy comes out in neutrinos (SN 1987A!)
  - ▷ unsolved problem: how is some of the neutrino energy deposited ($\sim 1\,\%$, 10^{44} J) in the envelope to eject the envelope and produce the supernova?
- leaves compact remnant (neutron star/black hole)

Thermonuclear Explosions



- occurs in accreting carbon/oxygen white dwarf when it reaches the Chandrasekhar mass
  - → carbon ignited under degenerate conditions; nuclear burning raises T, but not P
  - → thermonuclear runaway
  - → incineration and complete destruction of the star
- energy source is nuclear energy (10^{44} J)
- no compact remnant expected
- main producer of iron
- standard candle (Hubble constant, acceleration of Universe?)

but: progenitor evolution not understood

- ▷ single-degenerate channel: accretion from non-degenerate companion
- ▷ double-degenerate channel: merger of two CO white dwarfs

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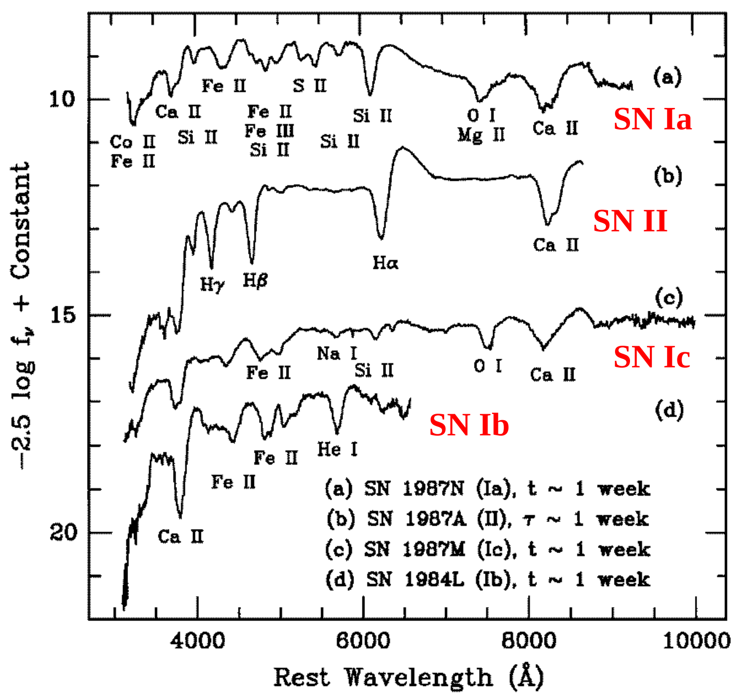
Supernova Classification



6.4.2 SUPERNOVA CLASSIFICATION

observational:

- Type I: no hydrogen lines in spectrum
- Type II: hydrogen lines in spectrum

theoretical:

- thermonuclear explosion of degenerate core
- core collapse → neutron star/black hole

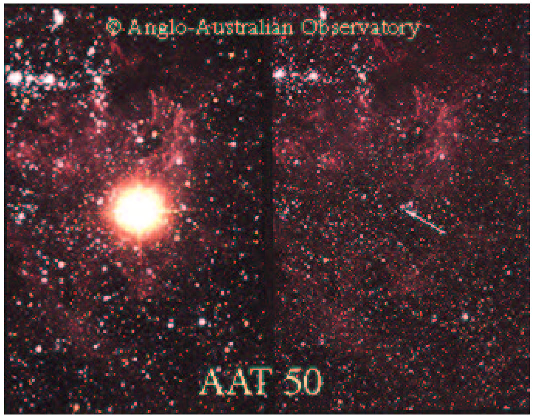
relation no longer 1 to 1 → confusion

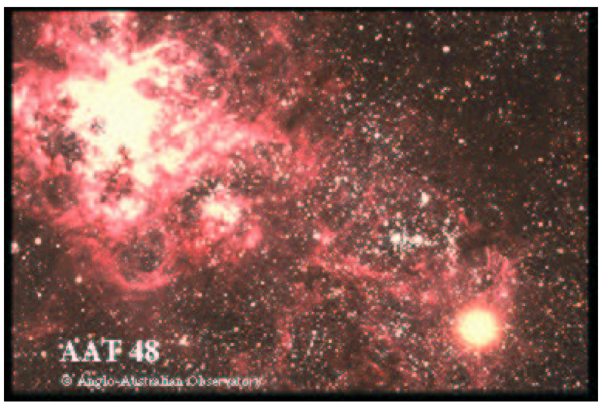
- Type Ia (Si lines): thermonuclear explosion of white dwarf
- Type Ib/Ic (no Si; He or no He): core collapse of He star
- Type II-P: "classical" core collapse of a massive star with hydrogen envelope
- Type II-L: supernova with linear lightcurve (thermonuclear explosion of intermediate-mass star? probably not!)

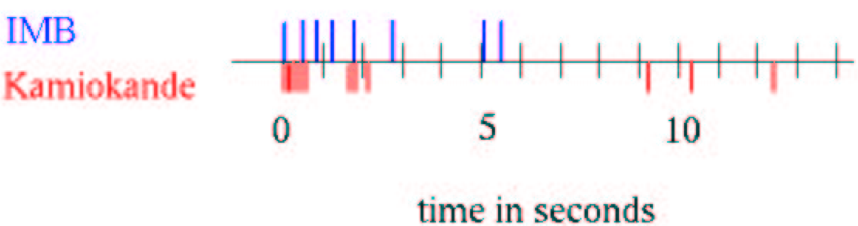
complications

- special supernovae like SN 1987A
- Type IIb: supernovae that change type, SN 1993J (Type II → Type Ib)
- some supernova "types" (e.g., IIn) occur for both explosion types ("phenomenon", not type; also see SNe Ic)
- new types: thermonuclear explosion of He star (Type Iab?)

SN 1987A (LMC)







Neutrino Signal

6.4.3 SN 1987A (ZG: 18-5)

- SN 1987A in the Large Magellanic Cloud (satellite galaxy of the Milky Way) was the first naked-eye supernova since Kepler's supernova in 1604
- long-awaited, but highly unusual, anomalous supernova
  - ▷ progenitor blue supergiant instead of red supergiant
  - ▷ complex presupernova nebula
  - ▷ chemical anomalies: envelope mixed with part of the helium core

Confirmation of core collapse

- neutrinos ($\bar{\nu}_e + p \rightarrow n + e^+$), detected with Kamiokande and IMB detectors
  - ▷ confirmation: supernova triggered by core collapse
  - ▷ formation of compact object (neutron star)
  - ▷ energy in neutrinos ($\sim 3 \times 10^{46}$ J) consistent with the binding energy of a neutron star

SUMMARY III(B): IMPORTANT STELLAR TIMESCALES

- dynamical timescale: $t_{dyn} \simeq \frac{1}{\sqrt{4G\rho}}$

$$\sim 30\,\mathrm{min}\,\left(\rho/1000\,\mathrm{kg\,m^{-3}}\right)^{-1/2}$$

- thermal timescale (Kelvin-Helmholtz): $t_{KH} \simeq \frac{GM^2}{2RL}$

$$\sim 1.5 \times 10^7\,\mathrm{yr}\,(M/M_\odot)^2\,(R/R_\odot)^{-1}\,(L/L_\odot)^{-1}$$

- nuclear timescale: $t_{nuc} \simeq \underbrace{M_c/M}_{\text{core mass}}\ \underbrace{\eta}_{\text{efficiency}}\ (Mc^2)/L$

$$\sim 10^{10}\,\mathrm{yr}\,(M/M_\odot)^{-3}$$

Example	t_{dyn}	t_{KH}	t_{nuc}
main-sequence stars			
a) $M = 0.1\,M_\odot$, $L = 10^{-3}\,L_\odot$, $R = 0.15\,R_\odot$	4 min	10^9 yr	10^{12} yr
b) $M = 1\,M_\odot$, $L = 1\,L_\odot$, $R = 1\,R_\odot$	30 min	15×10^6 yr	10^{10} yr
c) $M = 30\,M_\odot$, $L = 2 \times 10^5\,L_\odot$, $R = 20\,R_\odot$	400 min	3×10^3 yr	2×10^6 yr
red giant ($M = 1\,M_\odot$, $L = 10^3\,L_\odot$, $R = 200\,R_\odot$)	50 d	75 yr	
white dwarf ($M = 1\,M_\odot$, $L = 5 \times 10^{-3}\,L_\odot$, $R = 2.6 \times 10^{-3}\,R_\odot$)	7 s	10^{11} yr	
neutron star ($M = 1.4\,M_\odot$, $L = 0.2\,L_\odot$, $R = 10\,\mathrm{km}$, $T_{eff} = 10^6\,K$)	0.1 ms	10^{13} yr	

SUMMARY V: THE END STATES OF STARS

Three (main) possibilities

- the star develops a degenerate core and nuclear burning stops (+ envelope loss) → degenerate dwarf (white dwarf)
- the star develops a degenerate core and ignites nuclear fuel explosively (e.g. carbon) → complete disruption in a supernova
- the star exhausts all of its nuclear fuel and the core exceeds the Chandrasekhar mass → core collapse, compact remnant (neutron star, black hole)

Final fate as a function of initial mass (M_0) for $Z = 0.02$

$M_0 \lesssim 0.08\,M_\odot$	no hydrogen burning (degeneracy pressure + Coulomb forces)	planets, brown dwarfs
$[0.08, 0.48]\,M_\odot$	hydrogen burning, no helium burning	degenerate He dwarf
$[0.48, 8]\,M_\odot$	hydrogen, helium burning	degenerate CO dwarf
$[8, 13]\,M_\odot$	complicated burning sequences, no iron core	neutron star
$[13, 80]\,M_\odot$	formation of iron core, core collapse	neutron star, black hole
$M_0 \gtrsim 80\,M_\odot$	pair instability? complete disruption?	no remnant
also (?) $[6, 8]\,M_\odot$	degenerate carbon ignition possible (but unlikely), complete disruption	no remnant

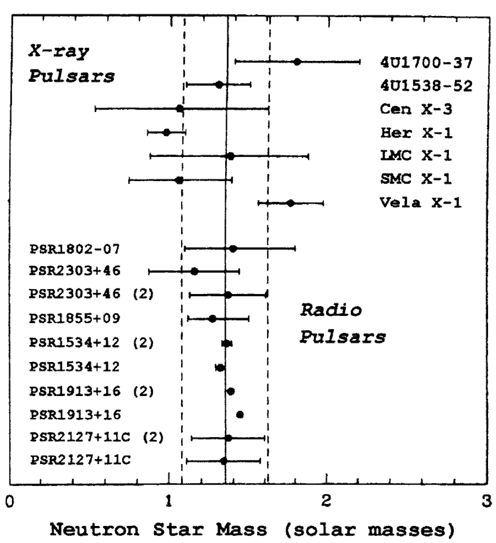
6.4.4 NEUTRON STARS (ZG: 17-2; CO: 15.6)

- are the end products of the collapse of the cores (mainly Fe) of massive stars (between 8 and $\sim 20\,M_\odot$)
- in the collapse, all nuclei are dissociated to produce a very compact remnant mainly composed of neutrons and some protons/electrons

Note: this dissociation is endothermic, using some of the gravitational energy released in the collapse

▷ these reactions undo all the previous nuclear fusion reactions

- since neutrons are fermions, there is a maximum mass for a neutron star (similar to the Chandrasekhar mass for white dwarfs), estimated to be between $1.5 - 3\,M_\odot$
- typical radii: 10 km (i.e. density $\sim 10^{18}\,\mathrm{kg\,m^{-3}}$!)



6.4.5 SCHWARZSCHILD BLACK HOLES (ZG: 17-3; CO: 16)

- event horizon: (after Michell 1784)

▷ the escape velocity for a particle of mass m from an object of mass M and radius R is $v_{esc} = \sqrt{\dfrac{2GM}{R}}$ ($11\,\mathrm{km\,s^{-1}}$ for Earth, $600\,\mathrm{km\,s^{-1}}$ for Sun)

▷ assume photons have mass: $m \propto E$ (Newton's corpuscular theory of light)

▷ photons travel with the speed of light c

$\rightarrow$ photons cannot escape, if $v_{esc} > c$

$$\rightarrow \boxed{R < R_s \equiv \frac{2GM}{c^2}} \text{ (Schwarzschild radius)}$$

▷ $R_s = 3\,\mathrm{km}\,(M/\,M_\odot)$

Note: for neutron stars $R_s \simeq 5\,\mathrm{km}$; only a factor of 2 smaller than R_{NS} $\rightarrow$ GR important

Orbits near Schwarzschild Black Holes