Collapse and final explosions

Stars with initial mass of less then ~ $9M_\odot$ (*this limit depends strongly on mass loss*) develop degenerate cores and if shell sources cannot increase M_c to ~M_{ch} the star becomes a WD.

Other stars undergo core collapse (such as those with neutron stars as remnants) or explosions, thereby ejecting a large part of their mass (supernova).

Evolution of the C-O core

- Further evolution details depend on whether C-O core becomes degenerate or not in the ensuing contraction phase.

  Estimating critical core mass M_{crit}, which determines whether contraction will increase T_c or if the core becomes degenerate:

- consider (approximate) EOS interpolating between both (non-deg. – degen.) regimes:

P dominated by non-deg. e^- (μ_e≈2, μ_0≥12)

rel.→non-rel. 10^{15}-10^{13}

ρ>>10^6gcm^{-3} ρ<<10^6gcm^{-3} 4/3≤γ≤5/3

$$P \approx P_e = \frac{\Re}{\mu_e}\varrho T + K_\gamma \left(\frac{\varrho}{\mu_e}\right)^\gamma$$

- rough estimate of **central$_0$ values** from hydrostatic equation

$$P_0 \approx \frac{GM_c\bar\varrho}{R_c} = fGM_c^{2/3}\varrho_0^{4/3}$$

$\bar\varrho = 3M_c/(4\pi R_c^3)$ ~ ϱ_0

$f(\overline{\rho}/\rho_0) = \text{constant}$

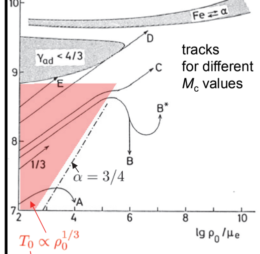
use EOS for P_0 →

$$\frac{\Re}{\mu_e}T_0 = \underbrace{fGM_c^{2/3}\varrho_0^{1/3}}_{\text{dominates for non-degeneracy}} - \underbrace{K_\gamma\varrho_0^{\gamma-1}\mu_e^{-\gamma}}_{} .$$

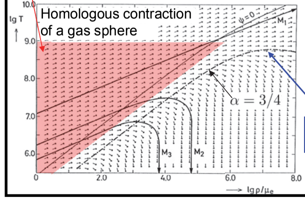
both terms are about equal for high-degeneracy

Collapse and final explosions

Evolution of the C-O core



$T_0 \propto \rho_0^{1/3}$



estimate T_{0max} for $M_c < M_{crit}$ in non-relativistic regime:

$$M_{crit} = \left(\frac{K_{4/3}}{fG}\right)^{3/2} \mu_e^{-2} \qquad \gamma = 5/3$$

$$\frac{\Re}{\mu_e}T_0 = fGM_c^{2/3}\varrho_0^{1/3} - K_\gamma\varrho_0^{\gamma-1}\mu_e^{-\gamma} .$$

$$\downarrow$$

$$\Re T_0 = K_{4/3}\left(\frac{M_c}{M_{crit}}\right)^{2/3}\left(\frac{\varrho_0}{\mu_e}\right)^{1/3} - K_{5/3}\left(\frac{\varrho_0}{\mu_e}\right)^{2/3}$$

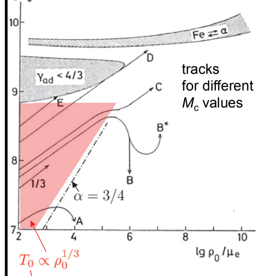
$$\Big\downarrow \varrho_{0max}$$

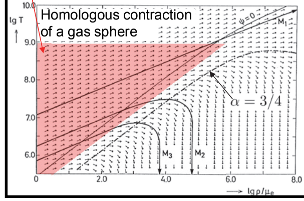
$$T_{0max} = \frac{1}{4\Re}\frac{K_{4/3}^2}{K_{5/3}}\left(\frac{M_c}{M_{crit}}\right)^{4/3} \approx 0.5\times10^9\,\mathrm{K}\left(\frac{M_c}{M_{crit}}\right)^{4/3}$$

for cores with $M_c \lesssim M_{crit}$ central $T_0 \lesssim 0.5\times10^9\,\mathrm{K}$.

Collapse and final explosions

Evolution of the C-O core





$$\frac{\Re}{\mu_e}T_0 = fGM_c^{2/3}\varrho_0^{1/3} - K_\gamma\varrho_0^{\gamma-1}\mu_e^{-\gamma}$$

describes $T_0(\rho_0)$ for given M_c.

- non-degenerate region: $T_0 \propto \rho_0^{1/3};\ T_0 \propto M_c^{2/3}$
- for low ρ_0 and small M_c the temperature T_0 increases up to a maximum value T_{0max}, after which it decreases until T_0→ 0 (A, B; M_3, M_2 in Ch. 28).

- with ρ_0↑ relativistic degeneracy becomes important; we rewrite EOS as ($\gamma = 4/3 + \chi$ with $\chi \to 0$ for $\varrho/\mu_e > 10^7\,\mathrm{g\ cm^{-3}}$):

$$\frac{\Re}{\mu_e}T_0 = \varrho_0^{1/3}\left(fGM_c^{2/3} - K_{(4/3+\chi)}\mu_e^{-(4/3+\chi)}\varrho_0^\chi\right)$$

this shows that T_0 increases again with $\rho_0^{1/3}$ for

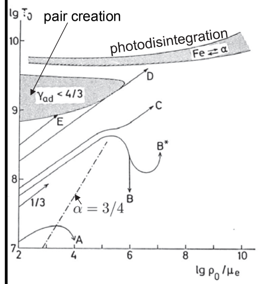
$$M_c > \underline{M_{crit} = \left(\frac{K_{4/3}}{fG}\right)^{3/2} \mu_e^{-2}} \quad \approx M_{Ch}$$

if $M_c \lesssim M_{Ch}$: T_0 → T_{0max} & decreases afterwards

if $M_c \gtrsim M_{Ch}$: T_0 continuously increases with $\rho_0^{1/3}$.

Collapse and final explosions

Evolution of the C-O core



(A, B): $M_c < M_{crit}$ ≈ M_{Ch}
shell-burning source(s) cannot increase core mass to M_{Ch}: T_0 ↑to T_{0max} until core becomes degenerate and core cools down to become a WD. (Binary: accreting WD→M_c>M_{Ch}→SN Ia)

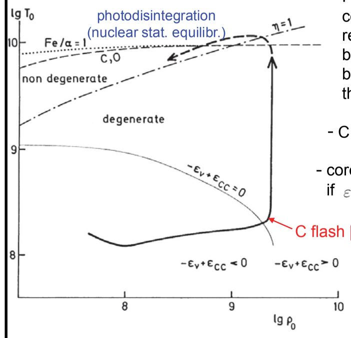
(B*): initially $M_c < M_{crit}$, but shell burning brings M_c≈ M_{Ch} core becomes degenerate and cools after T_{0max} . With ρ_0 increasing with M_c C-burning starts, e.g. by pycnonuclear reactions, in degenerate core → C flash (explosive: type 1.5 SN). This is the case for stars with typical masses $4 \lesssim M/M_\odot \lesssim 8$.

(C, D, M_1): $M_{crit} < M_c \lesssim 40M_\odot$
evolution track misses region of non-relativistic degeneracy region→core heats up. If $M_c \lesssim 4M_\odot$ e^- capture by Ne & Mg reduces P_0 → core collapse. For $M_c \gtrsim 4M_\odot$ photodisintegration of nuclei brings $\gamma_{ad} < 4/3$ (dynamically unstable) → also core collapse (may lead to *neutron-star* formation and ejection of envelop → *type II supernova*).

(E): $M_c \gtrsim 40M_\odot$ also C burning in non-degenerate core, but crosses later region of pair creation (photon energy so large that it can create e^- - e^+ pair) → $\gamma_{ad} < 4/3$ → core collapse until T so high that O burning starts → may stop collapse, which could lead to star explosion; if star does not explode, the collapse would lead evolution into region of photodisintegration, and event continue as in (D).

Collapse and final explosions

The carbon flash (B*)



C flash [@ ρ_0 ~ 2 x 10^9 gcm^{-3}]

- For $M \geq 8M_\odot$ shell-burning source increased core mass nearly to M_{Ch}, thereby also increasing ρ_0; released energy of core contraction is transported by e$^-$ conduction towards centre, where $T_0<T_{max}$ because of neutrino losses, which carry outwards the energy. Once ρ is high enough C burning ignites.
- C ignition either in centre or shell of T_{max}
- core stability crucially depends on neutrino losses ε_ν ; if $\varepsilon_c \gtrsim \varepsilon_\nu$ → core becomes unstable →(violant) C flash

How violent is C flash:
for a mixture of equal C & O, C burning releases ~ 2.5x10^{17}erg/g and O twice as much.
If all this energy is used to heat the core, it can reach temperatures as indicated by the dashed curve, labelled "C,O"; at this high temperatures, T~10^{10}K we have photodisintegration.

Collapse and final explosions

Photodisintegration and **nuclear statistical equilibrium**

@ T about 10^9-10^{10}K photons γ so energetic (MeV) as to cause photodisintegration (**photo-dissociation**) in the nuclei in the gas (α decay) , such as, for example,

$$^{32}\mathrm{S}+\gamma \to {}^{28}\mathrm{Si}+{}^{4}\mathrm{He}\ .$$

endothermic reaction (Q<0)

$$^{28}\mathrm{Si}+{}^{4}\mathrm{He} \rightleftarrows {}^{32}\mathrm{S}+\gamma\ .$$

exothermic reaction (Q>0) energetically favourable to shift equilibr. to the right.

Similar reactions:

$$\begin{aligned} ^{32}\mathrm{S}+{}^{4}\mathrm{He} &\rightleftarrows {}^{36}\mathrm{Ar}+\gamma\,, \\ ^{36}\mathrm{Ar}+{}^{4}\mathrm{He} &\rightleftarrows {}^{40}\mathrm{Ca}+\gamma\,, \\ &\vdots \\ ^{52}\mathrm{Fe}+{}^{4}\mathrm{He} &\rightleftarrows {}^{56}\mathrm{Ni}+\gamma\,. \end{aligned}$$

Processes occur essentially in equilibrium (EQ) with similar numbers of nuclei being dissociated and created; EQ is eventually shifted to heavier nuclei (> E$_b$):
quasi-equilibrium processes (misleadingly called *silicon burning*).

Similar reaction(s):
(neon burning)

$$^{20}\mathrm{Ne}+\gamma \to {}^{16}\mathrm{O}+\alpha \quad ,$$

$$\vdots$$

$$\gamma + {}^{56}_{26}\mathrm{Fe} \rightleftarrows 13\alpha + 4\mathrm{n} \quad . \qquad ({}^{52}\mathrm{Fe}+{}^{4}\mathrm{He} \rightleftarrows {}^{56}\mathrm{Ni}+\gamma\,.)$$

Collapse and final explosions

Nuclear statistical equilibrium (in a plasma of photodisintegration)

@ T about 10^{10}K photons γ so energetic as to break up nuclei by α deacy, e.g. :

$$^{20}\mathrm{Ne}+\gamma \rightleftarrows {}^{16}\mathrm{O}+\alpha$$

Processes of disintegration (dissociation) and inverse reaction similar to ionization and recombination of atoms: statistical equilibrium can be describes via SAHA equation, ie

$$\frac{n_\mathrm{O} n_\alpha}{n_\mathrm{Ne}} = \frac{1}{h^3}\left(\frac{2\pi m_\mathrm{O} m_\alpha kT}{m_\mathrm{Ne}}\right)^{3/2} \frac{G_\mathrm{O} G\alpha}{G_\mathrm{Ne}}\, \mathrm{e}^{-Q/kT}\ ,$$

where G_O, G_α and G_Ne are the statistical weights, while Q is the difference of binding energies

$$Q = (m_\mathrm{O}+m_\alpha-m_\mathrm{Ne})c^2 \quad .$$

Collapse and final explosions

Nuclear statistical equilibrium (in a plasma of photodisintegration)

@ T about 10^{10}K photons γ so energetic as to break up nuclei by α deacy, e.g. :

$$^{20}\mathrm{Ne}+\gamma \to {}^{16}\mathrm{O}+\alpha \quad ,$$

$$\vdots$$

^{56}Fe plays important role, because it is the nucleus with highest binding energy.

2p+2n

$$\gamma + {}^{56}_{26}\mathrm{Fe} \rightleftarrows 13\alpha + 4\mathrm{n} \quad .$$

behave like ionization and recombination

→ Nuclear statistical equilibrium defines ratio n_Fe/n_α

$$\begin{aligned} \gamma + (Z,A) &\rightleftarrows (Z-2,A-4)+\alpha\,, && (13x) \\ \gamma + (Z,A) &\rightleftarrows (Z,A-1)+\mathrm{n} && (4x) \end{aligned}$$

(13+4) Saha-like equations combined

(1) $$\frac{n_\alpha^{13} n_\mathrm{n}^4}{n_\mathrm{Fe}} = \frac{G_\alpha^{13} G_\mathrm{n}^4}{G_\mathrm{Fe}} \left(\frac{2\pi kT}{h^2}\right)^{24} \left(\frac{m_\alpha^{13} m_\mathrm{n}^4}{m_\mathrm{Fe}}\right)^{3/2} \mathrm{e}^{-Q/kT}$$ with $Q=(13m_\alpha+4m_\mathrm{n}-m_\mathrm{Fe})c^2$

difference of binding energies

also

(2) $$\rho = m_\mathrm{u}\sum_i A_i n_i = (56 n_\mathrm{Fe}+4n_\alpha+n_\mathrm{n})m_\mathrm{u}$$

Note: for $^{56}_{26}$Fe : $n_\mathrm{p}/n_\mathrm{n} = 13/15$
$n_n/n_\alpha = 4/13$

→ for given ratio, e.g. $n_n/n_\alpha = 4/13$ (^{56}Fe), 2 equ. (1)+(2) for 2 unknowns n_Fe and n_α .

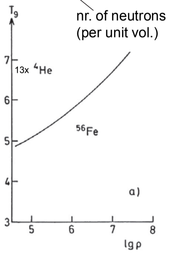
Collapse and final explosions

Nuclear statistical equilibrium (in a plasma of photodisintegration)

@ *T* about 10^{10}K photons γ so energetic as to create e^- - e^+ pairs = photodisintegration, e.g.

for given ratio, e.g. $n_n/n_\alpha = 4/13$ (^{56}Fe), and given ρ & *T*, nuclear equilibrium demands:

nr. of protons (per unit vol.) $\longrightarrow$ $\overline{Z}/\overline{N} = 13/15$ $\longleftarrow$ nr. of neutrons (per unit vol.)



In nuclear statistical equilibrium at moderate *T* one expects nuclei of the iron group, which with increasing *T* disintegrate into α particles, protons and neutrons.

Collapse and final explosions

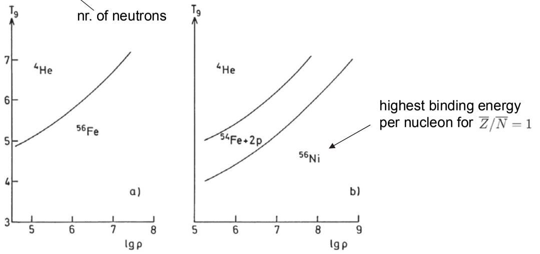
Nuclear statistical equilibrium (in a plasma of photodisintegration)

@ *T* about 10^{10}K photons γ so energetic as to create e^- - e^+ pairs = photodisintegration, e.g.

for given ratio, e.g. $n_n/n_\alpha = 4/13$ (^{56}Fe), and given ρ & *T*, nuclear equilibrium demands:

nr. of protons $\longrightarrow$ $\overline{Z}/\overline{N} = 13/15$ $\longleftarrow$ nr. of neutrons

$\overline{Z}/\overline{N} = 1$



In nuclear statistical equilibrium at moderate *T* one expects nuclei of the iron group, which with increasing *T* disintegrate into α particles, protons and neutrons.

Collapse and final explosions

Hydrostatic and convective adjustment during C flash

- during He flash star stays very close in hydrostatic equilibrium: convection removes energy.
- for C flash the situation is very different:
  in a single thermal run away, after the C flash ($\varepsilon_{\rm CC}$), *T*↑ so fast that additional reactions (O burning) take place; core regions is then so hot that statistical equilibrium between Fe & He is reached → degeneracy is removed, pressure increases → central regions expand.
- time scale τ_ε determined by change of *T* & internal energy ($\dot{T}/T \simeq \varepsilon_{\rm CC}/u$): $\tau_\varepsilon \simeq \dfrac{c_{\rm P}T}{\varepsilon_{\rm CC}}$

other (outer) core regions react on the hydrostatic time scale : $\tau_{\rm hyd} \simeq (G\overline{\rho})^{-1/2}$

if $\zeta := \tau_\varepsilon/\tau_{\rm hyd} >> 1 \longrightarrow$ core follows expansion quasi-hydrostatically

$\zeta << 1 \longrightarrow$ outer layers can not expand rapidly enough, **compression wave** will move outwards with c_s (outwards travelling shock wave)

convection in core will (a) transport part of surplus energy to outer layers, (b) bring new fuel into burning layers: $\tau_{\rm conv} \simeq \ell_{\rm m}/v_{\rm c}$

if $\xi := \tau_\varepsilon/\tau_{\rm conv} >> 1 \longrightarrow$ convection carries all energy away from core

in core $\rho > 10^8\ {\rm gcm}^{-3},\ T \simeq 3\times10^9{\rm K}$ one typically finds $\tau_\varepsilon \simeq 10^{-6}{\rm s},\ \tau_{\rm hydr} \simeq 0.1{\rm s}\ \&\ \tau_{\rm conv} \simeq 0.1{\rm s}.$

$\longrightarrow \zeta << 1,\ \&\ \xi << 1$ compression wave will start outwards and “convective blocking” (strong damping if motion is $v_{\rm c} \simeq c_{\rm s}$) limits spread of energy released in the core.

Collapse and final explosions

Combustion fronts (during C flash)

$\tau_\varepsilon \simeq 10^{-6}{\rm s}$ at the onset is rather short → burning proceeds at such high rates that fuel in mass shell is consumed essentially instantly & layer above has not time to adjust.

layer ahead is heated to ignition either by compression or energy transport, and flash proceeds outwards (burning confined to very thin layer) → outward moving combustion front.

Two different types of combustion front:

(a) matter in front enters discontinuity of compression wave (shock wave) with supersonic velocity and is compressed & heated; if matter is ignited combustion front coincides with shock front
→ detonation front

(b) if compression in shock wave does not ignite the fuel, then ignition temperature is reached due to energy transport (convection or conduction) → slower, subsonic motion of the burning front with a discontinuity in pressure and density drop (inwards!)
→ deflagration front
↳ speed it controlled by energy transport (convection or conduction).

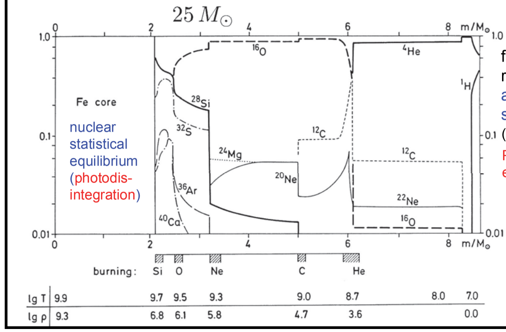
in both cases deviation from hydrostatic equilibrium mainly confined in thin shell of *P*,ρ discontinuity, and energy release.

Collapse and final explosions

Collapse of cores of massive stars (C,D): $M_{\rm Ch} < M_{\rm c} \lesssim 40 M_\odot$

core ‘misses’ non-relativistic degeneracy and heats up during contraction until ignition of next heavier element. Core is then either non-degenerate (large M_c) or degenerate, but still in a region “above” α=4/3, i.e. gravothermal heat capacity $c^* < 0$ → burning is stable!

after several cycles of nuclear burning and contraction, core will heat up to Si burning; burning in several shell sources produces layers of different chemical elements → onion-shell model.



nuclear statistical equilibrium (photodis-integration)

finally central regions of core reach *T* @ which abundances are determined by nuclear statistical equilibrium.

(a) $M_{\rm c} \gtrsim 4{\rm M}_\odot$

Photodisintegration and other effects (relativistic e⁻) → $\gamma_{\rm ad} < 4/3$

→ core collapse

(b) $M_{\rm c} \lesssim 4{\rm M}_\odot$

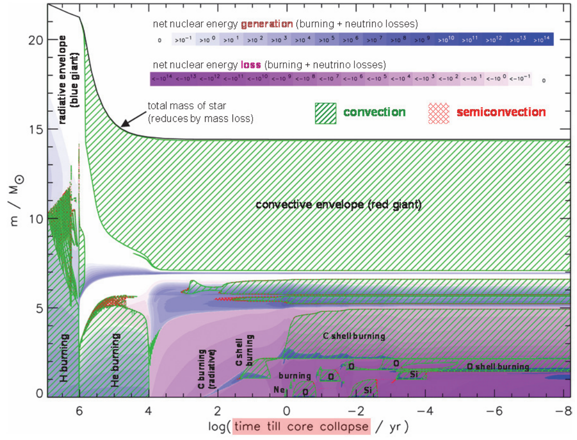
e⁻ capture by heavy nuclei (neutronization) → *P* reduced

→ core collapse with

$t_{\rm ff} \simeq 40\,{\rm ms}$ (@onset)

Collapse and final explosions

Collapse of cores of massive stars (C,D): $M_{\rm Ch} < M_{\rm c} \lesssim 40 M_\odot$



Collapse and final explosions

Inverse β decay (neutronization, e- capture) @ high densities

$$(Z, A) + e^- \to (Z-1, A) + \nu_e$$

High-energy e⁻ can combine with protons (in nuclei!) to form neutrons. High Fermi energy (sea) inhibits n-decay (no space left in 6-dim. phase space because of Pauli exclusion principle.)

Because process changes a proton into a neutron (although in a nucleus), this process is called **neutronization.**

Electron capture has two important consequences:

1) It reduces the number of electrons: μ_e gets larger. Thus, the pressure which is available to stabilize the gravitational contraction of the core is reduced. In other words, the Chandrasekhar mass limit decreases as μ_e increases.

2) The neutrinos produced in the reaction can leave the star. These neutrinos carry kinetic energy (usually of a few MeV) which is lost for the core. In fact, these neutrino losses keep the core at relatively low temperatures.

In summary:
the pressure and energy loss due to electron capture accelerates the contraction (collapse).

Collapse and final explosions

Reflection of infall (massive stars: C,D)

Because of infall ρ approaches that of neutron stars ($\rho \approx 10^{14}$ gcm^{-3}). Matter becomes incompressible (EOS is “stiff”).

Complete elastic reflection would bring whole collapse only to original state before the collapse; we need extra energy to expel the envelope.

Remnant (neutron star) is somewhat compressed by inertia beyond equilibrium state and afterwards, acting like a “spring”, it expands and pushes back the infalling matter.

This creates a pressure wave, steepening if it enters regions of lower density.

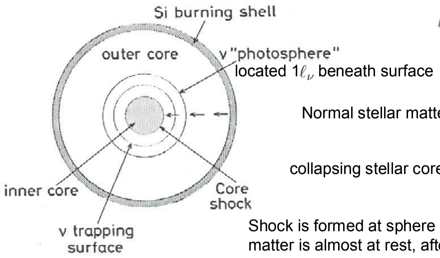
However, a substantial fraction of the energy in this rebounced pressure wave will be used up to disintegrate remaining Fe (in envelope) into free nucleons, i.e. only a small fraction of the (rebounced) kinetic energy remains in the shock wave for lifting the envelope (also major energy loss due to **neutrinos** → only 1% of initial kinetic energy available for lifting envelope).

During (core) collapse, neutrino production by **neutronization** becomes dominant. Because of large density, matter becomes opaque to neutrinos, i.e. free-mean path is reduced and so the neutrino velocity [for $\rho > 3\text{x}10^{11}$ gcm^{-3} **neutrinos are trapped**, because their velocities are smaller than the infall velocity (free-fall)] →influence further **neutronization**, i.e. **neutronization stops @ $\rho \sim 3\text{x}10^{12}$ gcm^{-3} (β equilibrium). Collapse stops @ $\rho > 10^{14}$ gcm^{-3}.**

Collapse and final explosions

Neutrinos in MeV range have mean free path (μ=1)

$$\ell_\nu = \frac{1}{n\sigma_\nu} = \frac{\mu m_u}{\varrho\sigma_\nu} \approx \frac{2\times10^{20}\mathrm{cm}}{\varrho}$$



Normal stellar matter : $\rho \simeq 1\,\mathrm{g\,cm^{-3}}$: $\ell_\nu \simeq 100\,\mathrm{parsec}$.

$\rho \simeq 10^6\,\mathrm{g\,cm^{-3}}$: $\ell_\nu \simeq 300\,\mathrm{R_\odot}$.

collapsing stellar core: $\rho \simeq 10^{14}\,\mathrm{g\,cm^{-3}}$: $\ell_\nu \simeq 20\,\mathrm{km}$.

$\longrightarrow$ reabsorbed within star.

infall velocity of matter (small arrows) equals velocity of outward neutrino diffusion

Shock is formed at sphere labelled "Core chock", within which matter is almost at rest, after sudden stop of core collapse, once density has reached nuclear matter density (ρ~10^{14} gcm^{-3}). Neutrinos interact with electrons (inelastic scattering) and neutrinos are thermalized, which brings also the weak interaction into equilibrium (already at ρ~10^{12} gcm^{-3}) - **homologous core**. Sound speed in core is larger than infall velocity. Where both velocities are the same = core shock boundary of homologous core. Thus the **sudden stop of collapse causes shock wave at the surface of the homologous core with *R* ~ 30km**.

Collapse and final explosions

Reflection of infall (massive stars: C,D) : Supernova explosion

Shock wave travels outwards through rest of collapsing iron core witch energy of about 10^{52} erg. Matter through which shock travels will be dissociated.

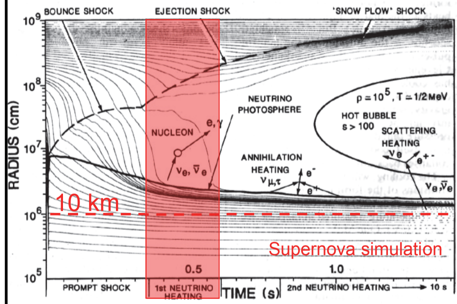


Figure shows radial motion of various layers and locations of travelling shock. Shock stalls @ *r*~500km, but gets revived again after about 0.5s, finally exploding the star.

Core (newly-born neutron star) cools rapidly via neutrino +anti-neutrino pair creation:

$$\gamma + \gamma \rightarrow \mathrm{e}^- + \mathrm{e}^+ \rightarrow \nu_\mathrm{e} + \overline{\nu}_\mathrm{e} \,,$$

leading to neutrino absorption by nucleons (p,n), thereby transferring energy (heated within ~0.3 s) to the matter which has previously been dissociated by the shock.

Material heated to energy values sufficient to overcome gravitational potential and can therefore be expelled from the star. This mechanism through **neutrino heating** is called "**delayed supernova**" mechanism. Time-dependent convection important for explosion mechanism!

Explosion expels matter outside "mass cut" ~ 1.6M$_\odot$ into ISM. Partially degenerate remnant is new neutron star consisting, after cooling, mainly of fully-degenerate neutrons.

Some properties of Supernovae (SN)

SN are amongst the brightest objects in the universe and can be brighter than a whole galaxy for weeks.

Energy of visible explosion: ~10^{51} erg (= 1 foe [10^(**f**ifty **o**ne) **e**rg])

Total energy : ~10^{53} erg (most in neutrinos)

Luminosity : ~$10^{9\text{-}10}$ L$_\odot$

SN events are rather rare: some 1 – 10 per century and galaxy.
(in our Galaxy only a few have been recorded, the last one in the 17th century: Kepler's SN: type Ia).

Classifications of Supernovae (SN)

Observational:

Type I : no H lines (depending on other spectral features: Ia, Ib, Ic,…)
Type II : hydrogen lines

SN progenitor

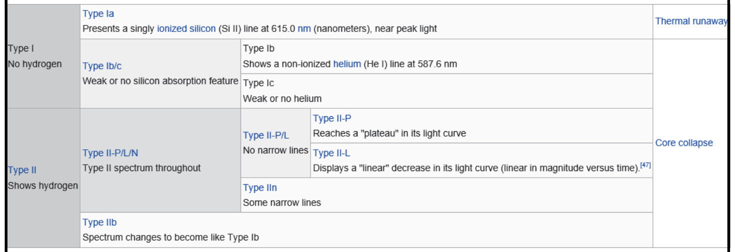
Type I : 2 possibilities
- Ia : **white dwarf accreting matter** from (massive) companion in binary system
- Ib,c: collapse of Fe core in star that blew its H (or He) envelope into space before the explosion

Type II : collapse of Fe core in normal massive stars (8 – 30 M$_\odot$)

electron-capture SN (Crab nebula?)

Classifications of Supernovae (SN)

Observational:

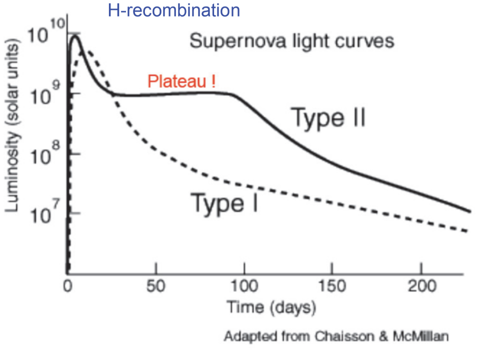


Type I No hydrogen	Type Ia Presents a singly ionized silicon (Si II) line at 615.0 nm (nanometers), near peak light			Thermal runaway
	Type Ib/c Weak or no silicon absorption feature	Type Ib Shows a non-ionized helium (He I) line at 587.6 nm		Core collapse
		Type Ic Weak or no helium		
Type II Shows hydrogen	Type II-P/L/N Type II spectrum throughout	Type II-P/L No narrow lines	Type II-P Reaches a "plateau" in its light curve	
			Type II-L Displays a "linear" decrease in its light curve (linear in magnitude versus time).[47]	
		Type IIn Some narrow lines		
	Type IIb Spectrum changes to become like Type Ib			

Classifications of Supernovae (SN)

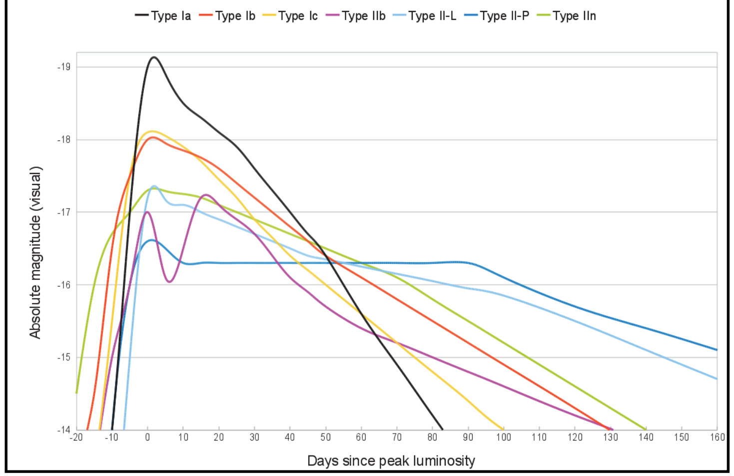
Energy sources: explosion   radiative decay: $^{56}Ni \rightarrow ^{56}Co \rightarrow ^{56}Fe$

H-recombination

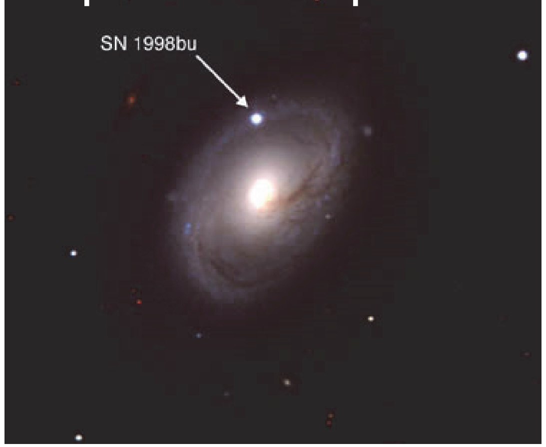


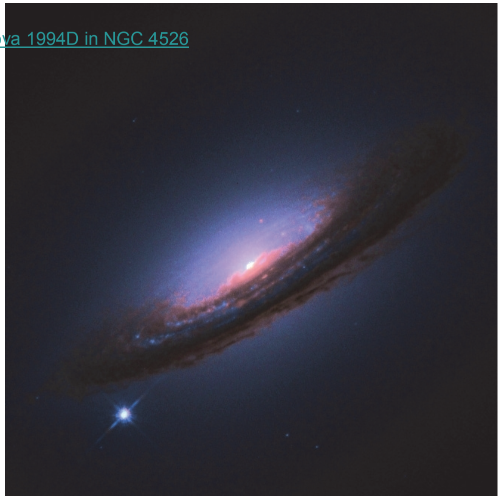
Adapted from Chaisson & McMillan

Classifications of Supernovae (SN)



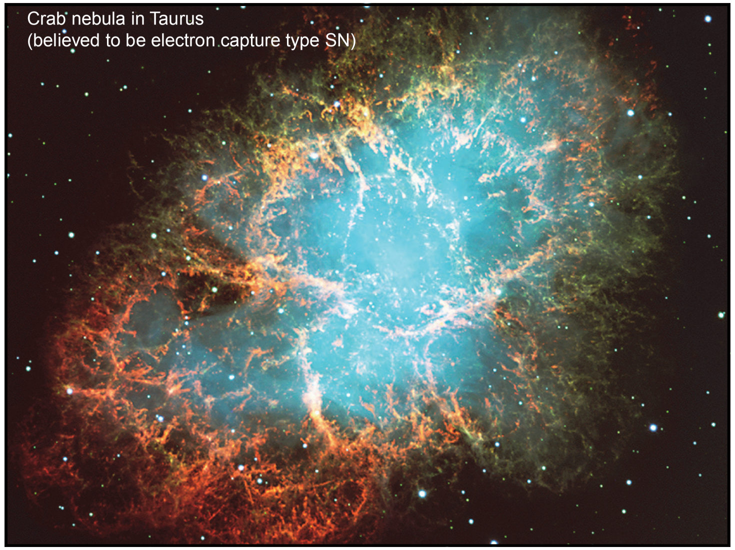
Supernova explosion





Supernova 1994D in NGC 4526

Supernova 2001cm in NGC 5965



Crab nebula in Taurus
(believed to be electron capture type SN)