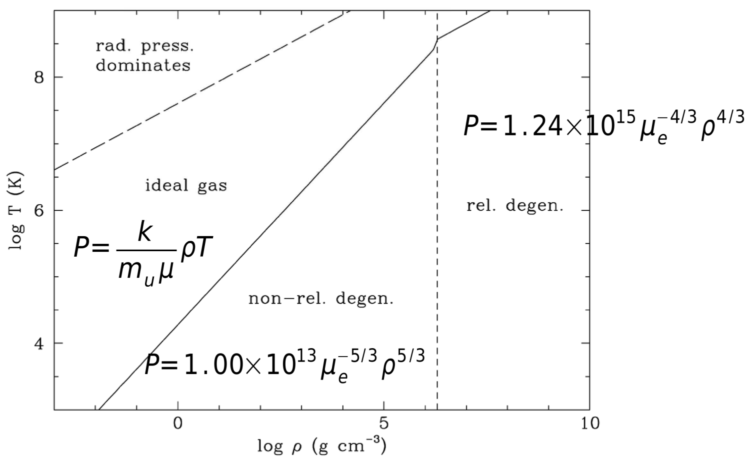
Outline of massive stars & supernovae

- Physics of massive stars
- Structure and evolution up to core collapse
- Core collapse, explosion
- Observational aspects of supernovae
- Circumstellar interaction of SNe
- Thermonuclear SNe = Type Ia SNe
- Gamma-ray bursts

Equation of state



Difference between massive and low mass stellar evolution = core evolution

$$P \approx \frac{k}{\mu_e m_p} \rho T + K_\gamma \left(\frac{\rho}{\mu_e}\right)^\gamma$$

$$\frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2} \Rightarrow P_c \approx \frac{GM_c \rho_c}{R_c}$$

$$P_c \approx fGM_c^{2/3} \rho_c^{4/3} \quad f=0.364 \quad \gamma=4/3$$

$$\frac{k}{\mu_e m_p} T_c \approx fGM_c^{2/3} \rho_c^{1/3} - K_\gamma \rho_c^{\gamma-1} \mu_e^{-\gamma}$$

Low density: perfect gas

$$kT_c \approx f\ G\mu_e m_p M_c^{2/3} \rho_c^{1/3}$$

High density: ER degenerate $\gamma=4/3$

$$M_{Ch} \approx \left(\frac{K_{4/3}}{fG}\right)^{3/2} \mu_e^{-2} = 5.85\,\mu_e^{-2}$$

Chandrasekhar mass

$$\frac{k}{m_p} T_c \approx \left(\frac{\rho_c}{\mu_e}\right)^{1/3} \left[K_{4/3} \left(\frac{M_c}{M_{Ch}}\right)^{2/3} - K_\gamma \left(\frac{\rho_c}{\mu_e}\right)^{\gamma-4/3} \right]$$

If $\gamma > 4/3$ then this has a max.

I. $M_c < M_{Ch}$ i.e., low mass stars: Gas NR $\gamma=5/3$

$$\frac{k}{m_p}T_c \approx K_{4/3}\left(\frac{\rho_c}{\mu_e}\right)^{1/3}\left(\frac{M_c}{M_{Ch}}\right)^{1/3} - K_{5/3}\left(\frac{\rho_c}{\mu_e}\right)^{2/3}$$

Temperature max at

$$\frac{\rho_{c,\max}}{\mu_e} = \left(\frac{K_{4/3}}{2K_{5/3}}\right)^{3}\left(\frac{M_c}{M_{Ch}}\right)^{2}$$

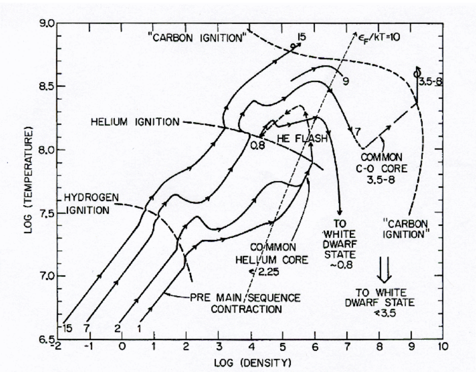
where

$$T_{c,\max} = \frac{m_p K_{4/3}^2}{4\,kK_{5/3}}\left(\frac{M_c}{M_{Ch}}\right)^{4/3} \approx 4.7\times10^{8}\left(\frac{M_c}{M_{Ch}}\right)^{4/3} \quad \mathrm{K}$$

II. $M_c > M_{Ch}$ i.e., high mass stars: Gas ER $\gamma=4/3+\varepsilon$ $\varepsilon<<1$

$$T_c \propto \left(\frac{\rho_c}{\mu_e}\right)^{1/3}$$

Core temperature rises monotonically



Conclusion

Main difference between low and high mass evolution:

Low mass stars ($M < 8\text{-}10\ M_{\odot}$) never reach high enough temperature to ignite carbon

Stellar nucleosynthesis

Carbon burning $T \sim (0.6\text{-}1.2)\times 10^{9}$ K

$^{12}C + {}^{12}C \rightarrow {}^{24}Mg^{*} \rightarrow {}^{24}Mg + n - 2.6$ MeV

$\rightarrow {}^{20}Ne + \alpha + 4.6$ MeV (~50%)

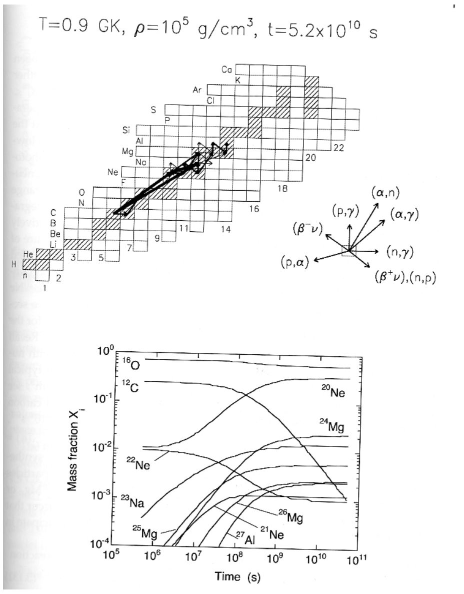
$\rightarrow {}^{23}Na + p + 2.2$ MeV (~50%)

$dQ/dt \propto T^{29}$

$^{12}C + {}^{12}C \rightarrow {}^{24}Mg^* \rightarrow {}^{24}Mg + n$

$\rightarrow {}^{20}Ne + \alpha$

$\rightarrow {}^{23}Na + p$



Neon burning $T \sim 1.5 \times 10^9$ K

First

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

Then

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

$^{20}Ne + \alpha \rightarrow {}^{24}Mg + \gamma$

In summary,

$2\,{}^{20}Ne \rightarrow {}^{16}O + {}^{24}Mg + 4.6$ MeV

$dQ/dt \propto T^{50}$

Oxygen burning   T ~2x10^9 K

I. Hydrostatic O-burning: Fusion dominates

$^{16}O + {}^{16}O \rightarrow {}^{28}Si + \alpha + 9.6$ MeV   (34 %)

$\rightarrow {}^{30}P + d - 2.4$ MeV   (5 %)

$\rightarrow {}^{31}P + p + 7.7$ MeV   (56 %)

$\rightarrow {}^{32}S + n - 1.5$ MeV   (5 %)

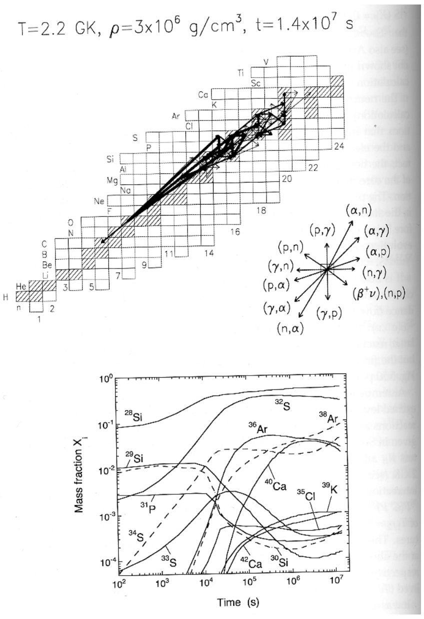
But, $^{31}P + \alpha \rightarrow {}^{28}Si + \gamma$ $dQ/dt \propto T^{33}$

II. Explosive O-burning: Photodisintegration dominates

$^{16}O + \gamma \rightarrow {}^{12}C + \alpha$

Main products:

^{28}Si and ^{32}S



Silicon burning $T \sim 3.5\times10^9$ K

I. Photodisintegration. Si melting

$^{28}Si(\gamma,\alpha)^{24}Mg(\gamma,\alpha)^{20}Ne(\gamma,\alpha)^{16}O(\gamma,\alpha)^{12}C(\gamma,2\alpha)\alpha$

II. Creates α particles

These are used to build heavier α elements

$^{28}Si(\alpha,\gamma)^{32}S(\alpha,\gamma)^{36}Ar(\alpha,\gamma)^{40}Ca(\alpha,\gamma)^{44}Ti(\alpha,\gamma)^{48}Cr(\alpha,\gamma)^{52}Fe(\alpha,\gamma)^{56}Ni$

Quasi equilibrium between forward and backward reactions

If run to nuclear statistical equilibrium (NSE) end-result will be iron peak elements

$dQ/dt \propto T^{49}$

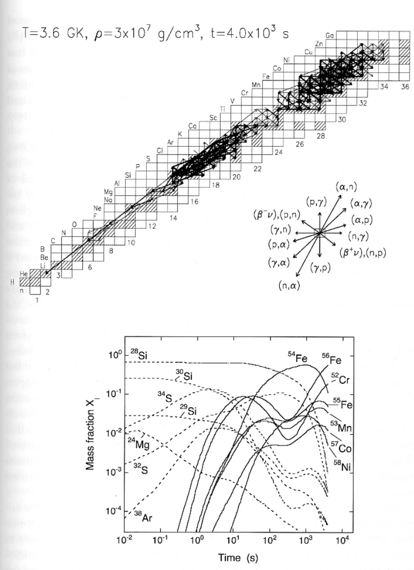


Fig. 5.52 Time-integrated net abundance flows (top) and abundance evolutions (bottom) for a constant temperature and density of T = 3.6 GK and $\rho = 3\times10^7$ g/cm^3, respectively. Such conditions are typical of core silicon burning in stars with an initial mass of $M = 25\ M_\odot$ and with initial solar metallicity. The reaction network is solved numerically until the silicon fuel is exhausted ($X_{28Si} <$ 0.001 after ≈ 4000 s). The arrows in the top part have the same meaning as in Fig. 5.44. The abundance flows in the top part of the figure reflect the existence of two quasiequilibrium clusters in the A = 25–40 and A = 46–64 mass ranges.

Saha: Ionization equlibrium

$$n_i + \gamma \leftrightarrow n_{i+1} + e^-$$

$$\frac{n_{i+1} n_e}{n_i} = \frac{G_{i+1} g_e}{G_i} \frac{(2\pi mkT)^{3/2}}{h^3} e^{-\chi_i/kT} \quad m = \frac{m_e m_{i+1}}{m_e + m_{i+1}}$$

Nuclear Statistical Equilibrium (NSE)

Remove (add) a neutron

$$n_{Z,A} + \gamma \leftrightarrow n_{Z,A-1} + n$$

$$\frac{n_{Z,A-1} n_n}{n_{Z,A}} = \frac{2G_{Z,A-1}}{G_{Z,A}} \frac{(2\pi m_{Z,A-1} m_n kT)^{3/2}}{h^3 m_{Z,A}^{3/2}} e^{-Q_n/kT}$$

$$Q_n = (m_{Z,A-1} + m_n - m_{Z,A}) c^2$$

$$\frac{n_{Z,A-1} n_n}{n_{Z,A}} = \frac{2G_{Z,A-1}}{G_{Z,A}} \left(\frac{A-1}{A}\right)^{3/2} \theta\, e^{-Q_n/kT}$$

$$\theta = (2\pi m_n kT)^{3/2}/h^3$$

Remove (add) a proton

$$n_{Z,A-1} + \gamma \leftrightarrow n_{Z-1,A-2} + p$$

$$\frac{n_{Z-1,A-1} n_n}{n_{Z,A-1}} = \frac{2G_{Z-1,A-2}}{G_{Z,A-1}} \left(\frac{A-2}{A-1}\right)^{3/2} \theta\, e^{-Q_p/kT}$$

$$Q_p = (m_{Z-1,A-2} + m_p - m_{Z,A-1}) c^2$$

Continue!

$$n_{Z,A} = G_{Z,A}\frac{A^{3/2} n_p^Z n_n^{A-Z}}{2^A}\theta^{1-A} e^{Q_{Z,A}/kT}$$

$$Q_{Z,A} = (Zm_p + (A-Z)m_n - m_{Z,A})c^2$$

$$\theta = (2\pi m_n kT)^{3/2}/h^3$$

+ Number conservation!

$$n_e = \sum_i Z_i n_{Z_i,A_i} \quad \rho = m_u \sum_i A_i n_{Z_i,A_i}$$

Define

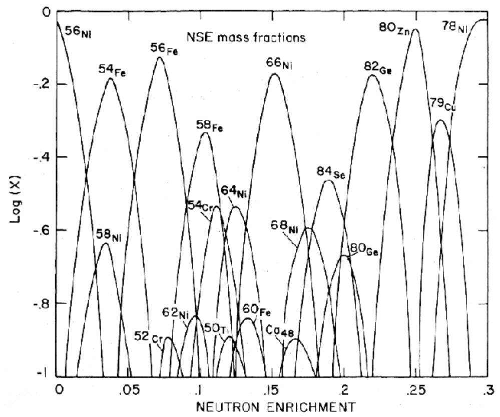
$$X_i = \frac{n_i A_i m_u}{\rho} \quad Y_e = \frac{n_e m_u}{\rho}$$

$$\sum_i X_i = 1 \quad Y_e = \sum_i Z_i \frac{X_i}{A_i}$$

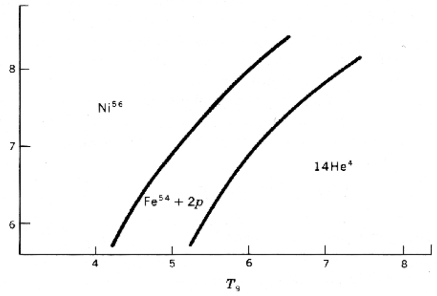
Neutron excess

$$\eta = \frac{n_n - n_p}{n_n + n_p} = 1 - 2Y_e$$

Rule: The most tightly bound nucleus for a given neutron excess is favored. For η=0 the most ^{56}Ni (28 n + 28 p, doubly magic) is most bound. For η=0.07 ^{56}Fe [(30 – 26)/56=0.071]



Photodisintegration



Neutrino cooling

T ~ m_e c^2/k ~ 5x10^9 K   electron/positron pair creation

$\gamma + e^{+/-} \rightarrow e^- + e^+$

$\gamma + Z \rightarrow e^- + e^+$

Most often

$e^- + e^+ \rightarrow 2\gamma$

Sometimes, weak interaction

$$e^+ + e^- \rightarrow \nu_e + \bar{\nu}_e$$

$$\sigma \approx 10^{-44} \left(\frac{E}{m_e c^2} \right)^2 \quad \text{cm}^2$$

Pair production

$$\varepsilon \approx 4.9 \times 10^{18} T_9^3 e^{-11.86/T_9} \quad T < 10^9$$

$$\varepsilon \approx 4.5 \times 10^{15} T_9^9 \quad T > 3 \times 10^9$$

Plasma neutrino cooling

Dispersion relation for a photon in a plasma

$$\omega^2 = k^2 c^2 + \omega_{pl}^2$$

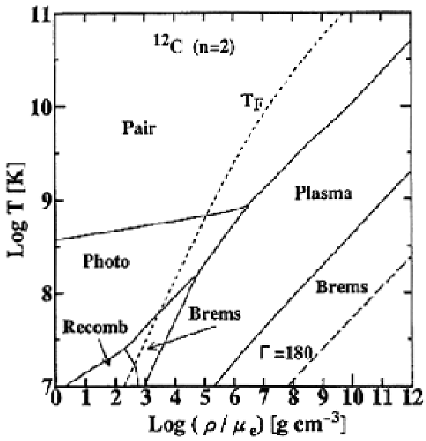
$$\omega_{pl} = \left(\frac{4\pi n_e e^2}{m_e} \right)^{1/2} = 5.6 \times 10^4 n_e^{1/2} \quad \text{Hz}$$

$$E^2 = p^2 c^2 + m^2 c^4$$

The photon behaves if it had a mass which can be used for pair production of neutrinos

Photo neutrino

$$\gamma + e^{-} \rightarrow e^{-} + \nu_e + \bar{\nu}_e$$

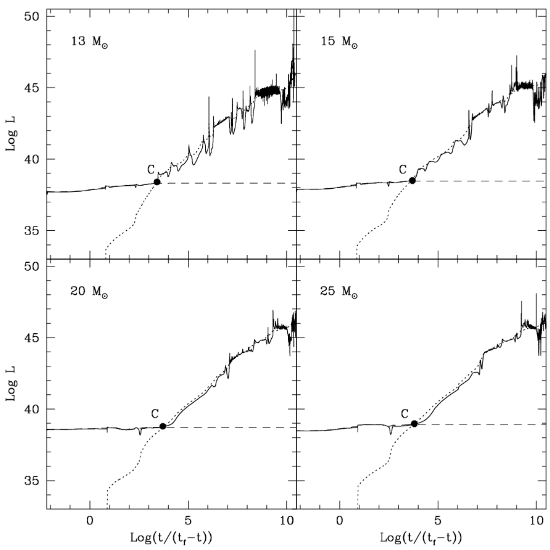


Pair most important

for massive stars

Plasma for lower masses

Neutrino vs photon luminosity



Carbon burning and

later dominated by

neutrino cooling!!

$$\tau_i = \frac{Y_i q_i}{\varepsilon_i}$$

Table 3: **Estimates of the duration of the advanced burning stages**

Burning stage	$q_i/10^{17}$ erg g^{-1}	Y_i	T_i 10^9 K	$\rho/10^6$ g cm^{-3}	ϵ_i erg g^{-1} s^{-1}	τ_i s
C	4.0	0.2	0.7	0.3	7.1×10^5	3.6×10^3 yrs
Ne	1.1	0.7	1.4	2.7	3.0×10^9	0.81 yrs
O	5.0	0.2	1.9	6.9	3.5×10^{10}	30 days
Si	1.9	0.5	3.4	39.3	2.4×10^{12}	0.5 days

15 M_o

Table 1: **Burning stages for a** 15 $M_\odot$ **star (WHW02)**

Fuel	Ashes	T 10^8 K	ρ g cm^{-3}	M $M_\odot$	L 10^3 $L_\odot$	R $R_\odot$	τ yrs
H	He, N	0.35	5.8	14.9	28.0	6.75	1.1×10^7
He	C,O	1.8	1.4×10^3	14.3	41.3	461.	2.0×10^6
C	Ne, Mg, O	8.3	2.4×10^5	12.6	83.3	803.	2.0×10^3
Ne	O, Mg, Si	16.3	7.2×10^6	12.6	86.5	821.	0.73
O	Si, S	19.4	6.7×10^6	12.6	86.6	821.	2.6
Si	Ni	33.4	4.3×10^7	12.6	86.5	821.	18 days

25 M_o

Table 2: **Same as above for a** 25 $M_\odot$ **star**

Fuel	Ashes	T 10^8 K	ρ g cm^{-3}	M $M_\odot$	L 10^3 $L_\odot$	R $R_\odot$	τ yrs
H	He	0.38	3.8	24.5	110.	9.2	6.7×10^6
He	C,O	2.0	7.6×10^2	19.6	182.	1030.	8.4×10^5
C	Ne, Mg	8.4	1.3×10^5	12.5	245.	1390.	5.2×10^2
Ne	O, Mg	15.7	4.0×10^6	12.5	246.	1400.	0.89
O	Si, S	20.9	3.6×10^6	12.5	246.	1400.	0.40
Si	Ni	36.5	3.0×10^7	12.5	246.	1400.	0.73 days

Mass loss I

Early type stars: O-B stars

Radiatively driven winds by UV radiation

UV resonance lines Most important Fe III-V

$v_W \approx 1000 - 3000$ km s^{-1} $dM/dt \approx 10^{-7} - 10^{-6}$ M_O yr^{-1}

Mass loss II

Red supergiants

Dust driven winds + pulsations (?)

$v_W \approx 10 - 50$ km s^{-1} $dM/dt \approx 10^{-6} - 10^{-4}$ M_O yr^{-1}

superwinds connected to pulsations (?)

$dM/dt \approx 10^{-4} - 10^{-3}$ M_O yr^{-1} duration $< 10^4$ yrs

Wolf-Rayet stars (post-MS stars No H left!)

Pulsations (?) + radiatively driven winds by UV radiation

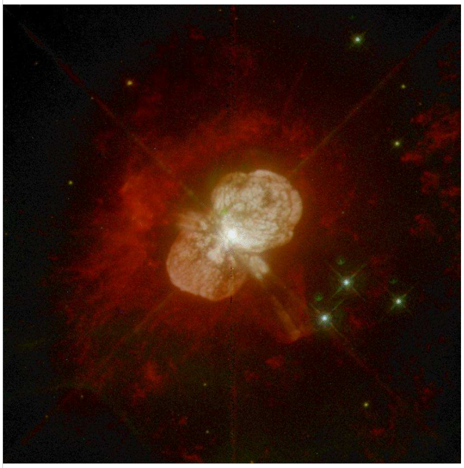
UV resonance lines

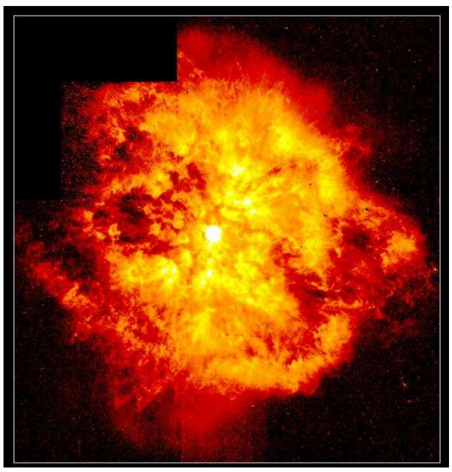
Most important Fe III-V

$v_W \approx 1000 - 3000$ km s^{-1} dM/dt $\approx 10^{-6} - 10^{-5}$ M_O yr^{-1}

$\tau_{OB} \sim 10^6$ yrs $\tau_{RSG} \sim 10^5$ yrs $\tau_{WR} \sim 10^5$ yrs

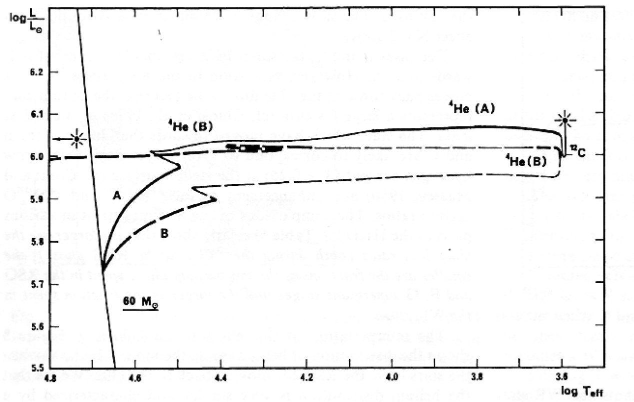
several M_O lost!





η Carinae LBV M ~ 100 M_O WR 124 Wolf-Rayet star M ~ 40 M_O

60 $M_\odot$



Without mass loss: O → BSG, LBV → RSG → SN

With: O → BSG → RSG → WR → SN

M > 60 $M_\odot$ O → LBV → WR → SN

Rotation

On MS v ~ 200 km s^{-1}

Break-up velocity:

$$\frac{V^2}{R} \approx \frac{GM}{R} \Rightarrow V_c \approx \left(\frac{GM}{R}\right)^{1/2}$$

I. Rotation → circulation → mixing

II. Rotation → flattening of star

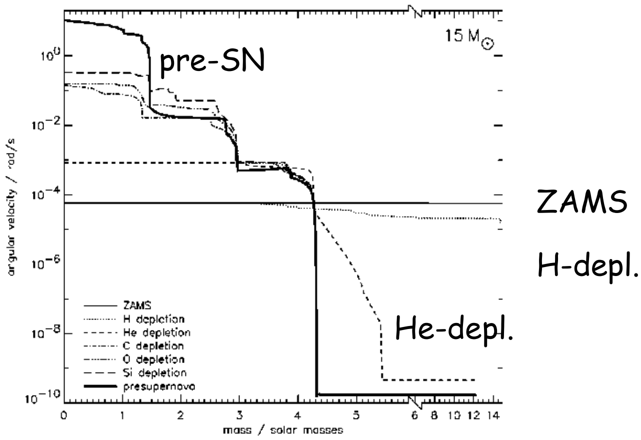
Flux follows grav. potential surfaces (von Zeipels theorem)

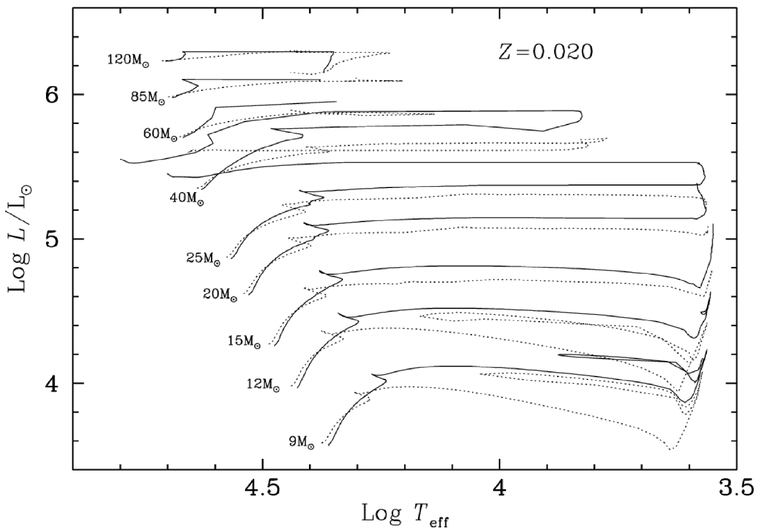
⇒ star more luminous at poles ⇒ more mass loss in polar directions

III. On MS solid body rotation

If angular momentum is conserved $\Omega \propto R^{-2}$

core contracts ⇒ spin-up H-envelope expands ⇒ slow down

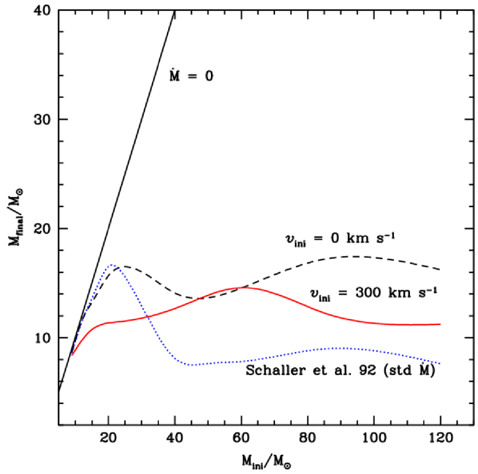




No rotation: $M(WR) \sim 37\ M_{\odot}$

With rotation: $M(WR) \sim 22\ M_{\odot}$

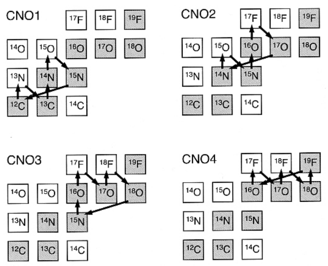
Final mass vs initial mass



Final mass independent of initial mass for large M!!

Mainly H-envelope lost. Core mass less affected ⇒ L ~ same

CNO burning in massive stars



$$^{12}C(p,\gamma)^{13}N(e^{+}\nu)^{13}C(p,\gamma)^{14}N(p,\gamma)^{15}O(e^{+}\nu)^{15}N(p,\alpha)^{12}C$$

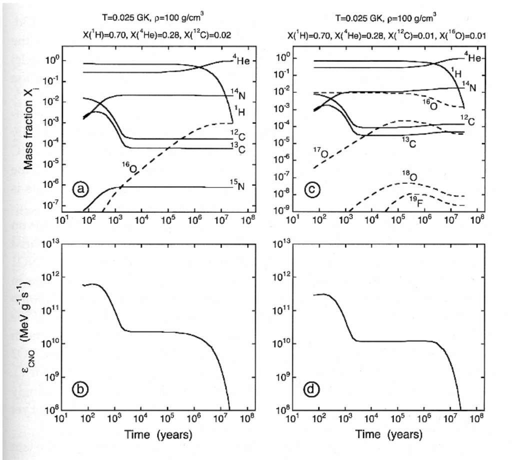
$$^{15}N(p,\gamma)^{16}O \qquad 0.1\ \%$$

$$^{16}O(p,\gamma)^{17}F(e^{+}\nu)^{17}O(p,\alpha)^{14}N$$

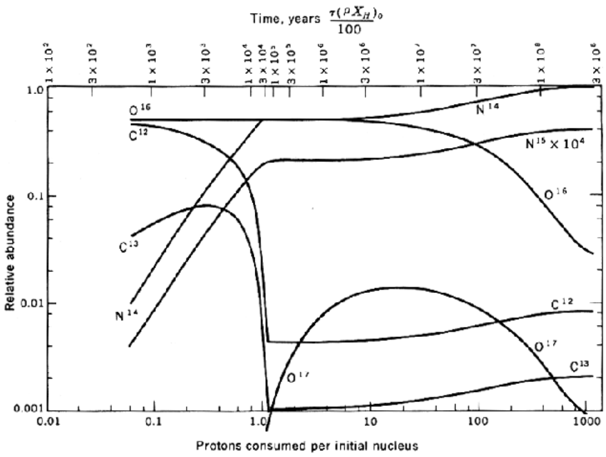
$$^{17}O(p,\gamma)^{18}F(e^{+}\nu)^{18}O(p,\gamma)^{19}F(p,\alpha)^{16}O \qquad 0.5\ \%$$

C converted to N and if running long enough also O to N

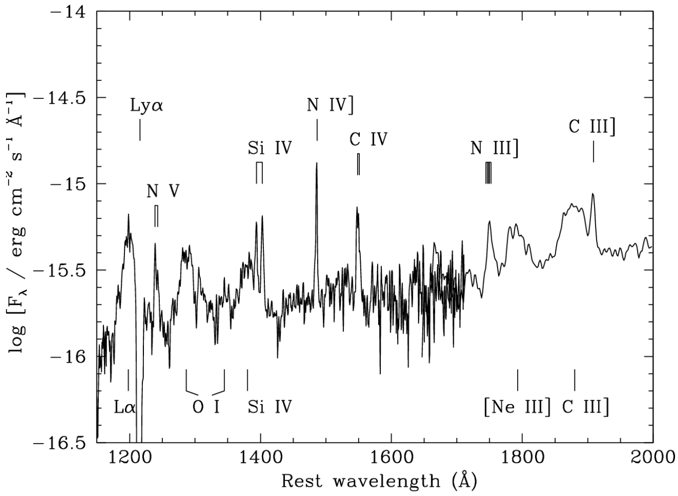
CNO burning in massive stars



C converted to N and if running long enough also O to N



SN 1998S Type IIn

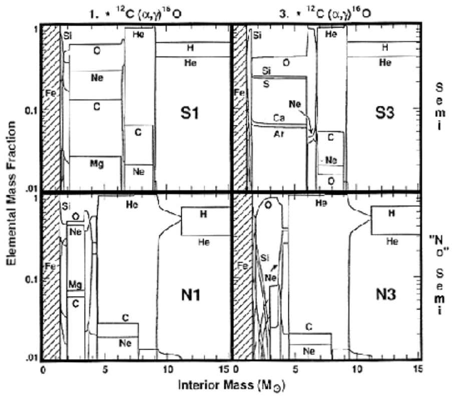


N/C ~ 6 (Sun N/C ~ 1/4)

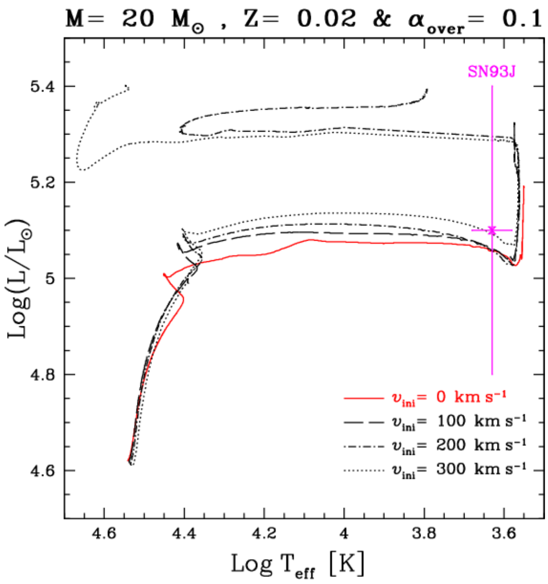
Uncertainties in nuclear reaction rates

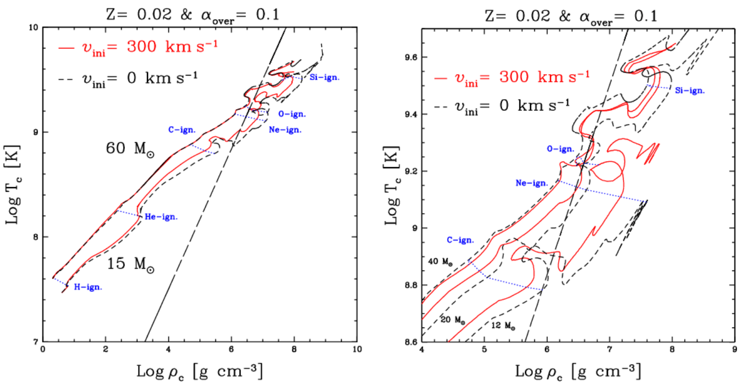
$^{12}C(\alpha,\gamma)^{16}O$ uncertain by factor of ~ 3

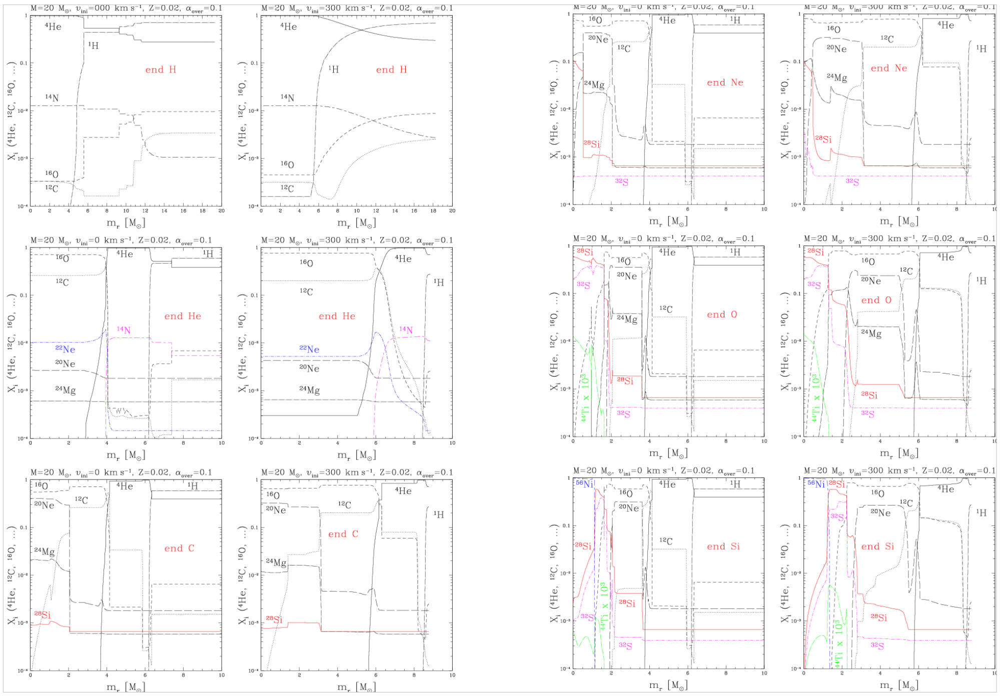
affects C/O and whole evolution after He burning



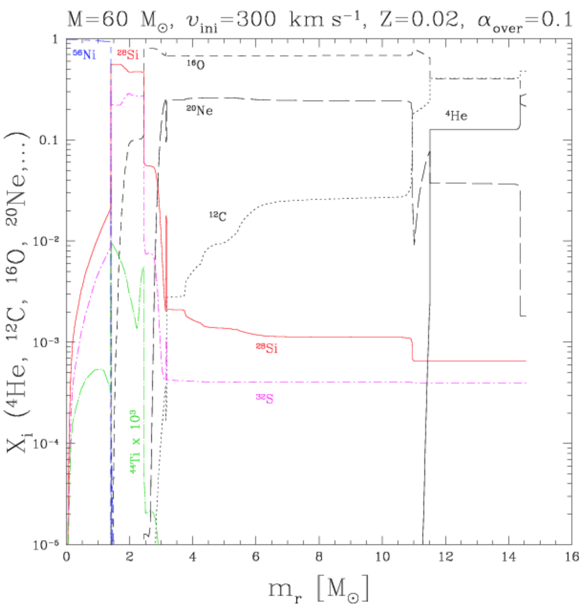
Example: 20 M


M= 20 M⊙ , Z= 0.02 & α_over= 0.1
SN93J
Log(L/L⊙)
Log T_eff [K]
v_ini= 0 km s⁻¹
v_ini= 100 km s⁻¹
v_ini= 200 km s⁻¹
v_ini= 300 km s⁻¹

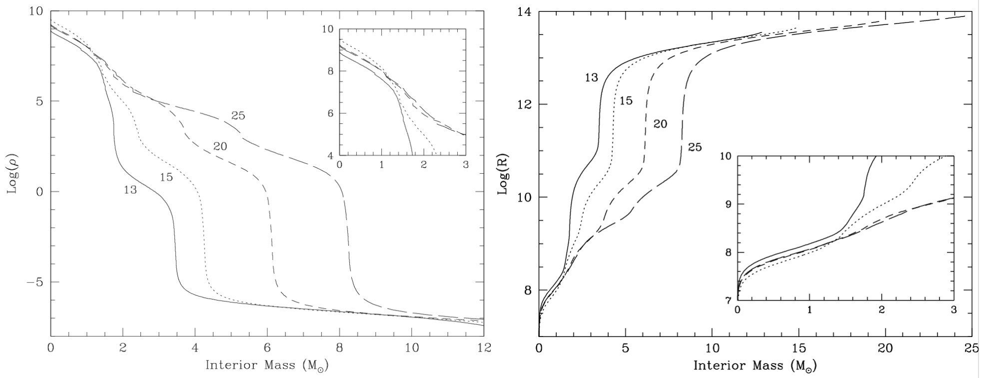

Z= 0.02 & α_over= 0.1
v_ini= 300 km s⁻¹
v_ini= 0 km s⁻¹
60 M⊙
15 M⊙
H-ign.
He-ign.
C-ign.
Ne-ign.
O-ign.
Si-ign.
Log T_c [K]
Log ρ_c [g cm⁻³]
Z= 0.02 & α_over= 0.1
v_ini= 300 km s⁻¹
v_ini= 0 km s⁻¹
40 M⊙
20 M⊙
12 M⊙
C-ign.
Ne-ign.
O-ign.
Si-ign.
Log T_c [K]
Log ρ_c [g cm⁻³]

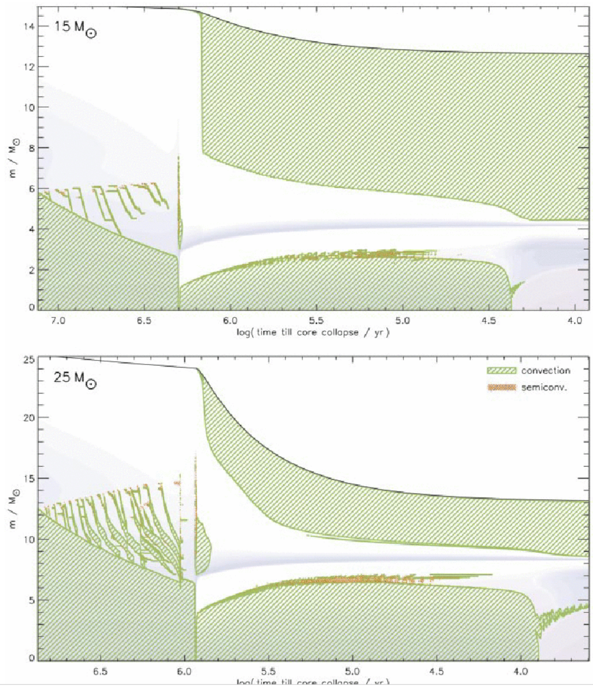

end H
end He
end C
end Ne
end O
end Si
m_r [M_⊙]

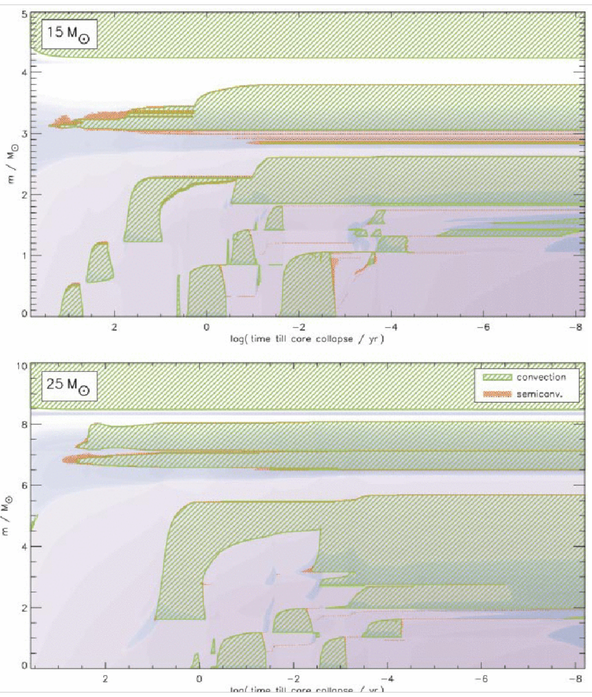
M = 60 M


M=60 M_⊙, υ_ini=300 km s⁻¹, Z=0.02, α_over=0.1
⁵⁶Ni
²⁸Si
¹⁶O
²⁰Ne
⁴He
¹²C
²⁸Si
³²S
⁴⁴Ti x 10³
X_i (⁴He, ¹²C, ¹⁶O, ²⁰Ne,...)
m_r [M_⊙]

Pre-SN structure






15 M$_\odot$
m / M$_\odot$
log(time till core collapse / yr)
25 M$_\odot$
convection
semiconv.
m / M$_\odot$