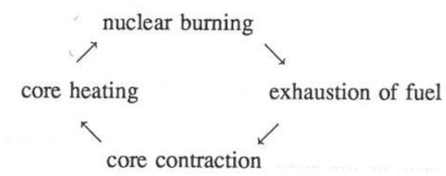
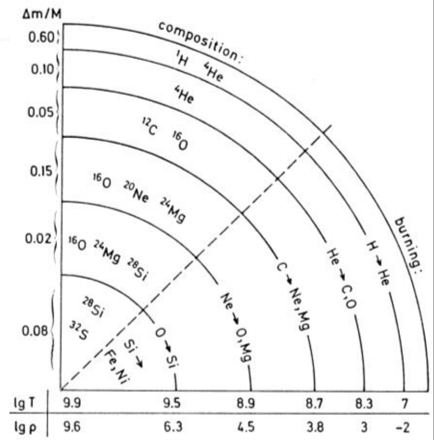
Later phases of core evolution
(of sufficiently massive stars)



Scheme: momentary nuclear burning will gradually consume all nuclei inside the convective core which serves as "fuel". Exhausted core contracts; this raises T_c until next higher burning is ignited, etc.

E.g., during 1st cycle (H-burning) star develops massive He core, inside which a much smaller C-O core is produced in the next cycle (He burning), and so on.

We have also seen that after core exhaustion the burning continues in a shell, which can survive several of the succeeding nuclear cycles, each of which generates a new shell source, such that several of them can simultaneously burn outwards through the star, with gradually heavier elements when going inwards from shell to shell
→ "onion skin model".



Later phases of core evolution
(of sufficiently massive stars)

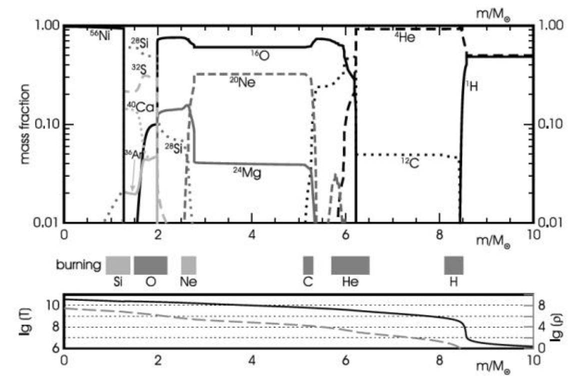


Fig. 36.4. The chemical composition in the interior of a highly evolved model of a population I star with an initial mass of $25M_{\odot}$, close to the end of hydrostatic nuclear burning. The mass at this time is reduced to $16M_{\odot}$ due to mass loss. In the upper panel the mass concentrations of important elements are plotted against the mass variable m. Below the abscissa, in the middle of the figure the approximate location of shell sources in different nuclear burning phases is indicated by the grey rectangles. In the lower panel the run of temperature ($\lg T$: scale at left axis) and density ($\lg \varrho$: right axis) is given to identify typical burning conditions for these nuclear shells (data courtesy R. Hirschi, published in Hirschi et al. 2004)

Later phases of core evolution

This simple picture of evolution (nuclear cycles) can be interrupted, either temporarily or for good, through

(a) cycles must come to an end, at the latest, when innermost core consist of ^{56}Fe and no further exothermic fusions are possible.

(b) Degeneracy in central region decouples thermal from mechanical evolution, and cycle of consecutive nuclear burnings is interrupted. Degeneracy develops in a dense core, with the central density ρ_c increased by the contraction between consecutive burnings. Next burning ignited by secondary effects, i.e. evolution of the surrounding shell source (T_c~M_c).

From homology [homologous contraction $\dot{r}/r = \dot{R}/R \rightarrow \mathrm{d}_m(\dot{r}/r) = 0 \rightarrow \mathrm{d}_t(r^{-1}\mathrm{d}_m r) = 0$] we obtain:

$$\frac{\dot{\rho}}{\rho} = -3\frac{\dot{r}}{r} \quad \& \quad \frac{\dot{P}}{P} = -4\frac{\dot{r}}{r} \quad \text{\& using} \quad \frac{\dot{\rho}}{\rho} = \alpha\frac{\dot{P}}{P} - \delta\frac{\dot{T}}{T} \longrightarrow \frac{\mathrm{d}T_c}{T_c} = \left(\frac{4\alpha-3}{3\delta}\right)\frac{\mathrm{d}\rho_c}{\rho_c}$$

depends critically on EOS; >0 for contraction

ideal gas: $\alpha = 1\,;\delta = 1 \;\rightarrow\; \mathrm{d}T_c/T_c = (1/3)(\mathrm{d}\rho_c/\rho_c) \rightarrow$ $T_c\uparrow$ for contraction.

degeneracy parameter $\psi = \psi(n_e/T^{3/2})\uparrow$ $\quad [\psi = \text{constant for } \mathrm{d}T/T = (2/3)(\mathrm{d}\rho/\rho)]$

degenerate gas: for critical value for $\alpha = 3/4$ (for finite δ) contraction **no longer** leads to $T_c\uparrow$.

(c) energy loss due to cooling neutrinos → decrease T_c → influence onset of burning.

Later phases of core evolution

(of sufficiently massive stars)

Typical timescales for nuclear burning

Table 35.1. The duration of burning stages (in years) in three models of different mass, taken from Limongi & Chieffi (2006). The beginning and end of each burning stage is defined as the times when 1% of the fuel has been burnt, respectively when its abundance has dropped to below 10^{-3}. (Data courtesy M. Limongi)

Burning:	$M = 15\,M_\odot$:	$M = 40\,M_\odot$:	$M = 120\,M_\odot$:
H	1.31×10^{7}	4.88×10^{6}	2.80×10^{6}
He	9.27×10^{5}	3.82×10^{5}	2.96×10^{5}
C	3.25×10^{3}	1.86×10^{2}	3.62×10^{1}
Ne	6.67×10^{-1}	1.34×10^{-1}	6.56×10^{-2}
O	3.59×10^{0}	1.59×10^{-1}	2.57×10^{-2}
Si	6.65×10^{-2}	1.47×10^{-3}	3.63×10^{-4}

$t_{nuc} \leq t_{KH}$ (C, Ne, O, Si)

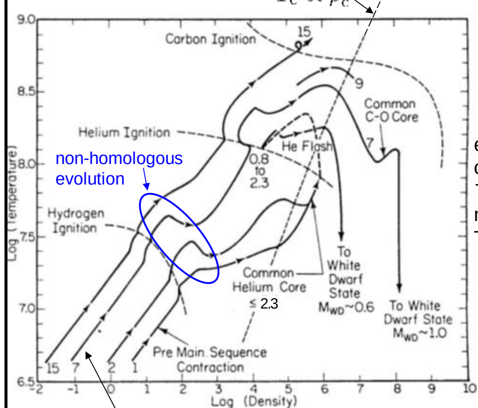
↓

core changes no longer reflected at surface.

Later phases of core evolution

Evolution of central regions

$T_c \propto \rho_c^{2/3}$ degeneracy



$T_c \propto \rho_c^{1/3}$

$\mathrm{d}\ln T_c = (4\alpha - 3)/(3\delta)\mathrm{d}\ln\rho$

in non-degenerate regions $T \sim \rho^{1/3}$;

non-homologous evolution because of structure changes due to radiation – convective core.

each contraction with $T \sim \rho^{1/3}$ brings centre closer to e$^-$ degeneracy; in degenerate regions T_c no longer increases, and the next burning is not reached by further contraction (if at all). This is more likely the case for low-mass stars.

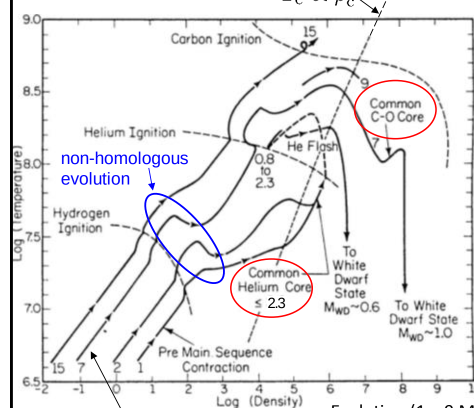
This happens the earlier in nuclear history the closer to degeneracy star has been @ ZAMS, i.e. which nuclear cycle is completed before star develops degenerate core depends on the stellar mass *M*.

Later phases of core evolution

Evolution of central regions

standard evolution computations suggest the following approximate limiting masses:

$T_c \propto \rho_c^{2/3}$ degeneracy



$T_c \propto \rho_c^{1/3}$

$\mathrm{d}\ln T_c = (4\alpha - 3)/(3\delta)\mathrm{d}\ln\rho$

$M < 2.3\ M_\odot$ develop degenerate He cores

$M \leq 9\ M_\odot$ develop degenerate C-O cores

$M > 9\ M_\odot$ C-O cores remain non-degenerate

after star developed degenerate core it has not necessarily reached very end of nuclear life, unless shell-source cannot sufficiently increase mass of degenerate core.

If shell source can increase core mass to at least to critical core mass M'_c, next burning is only delayed, and will be ignited in a later "flash".

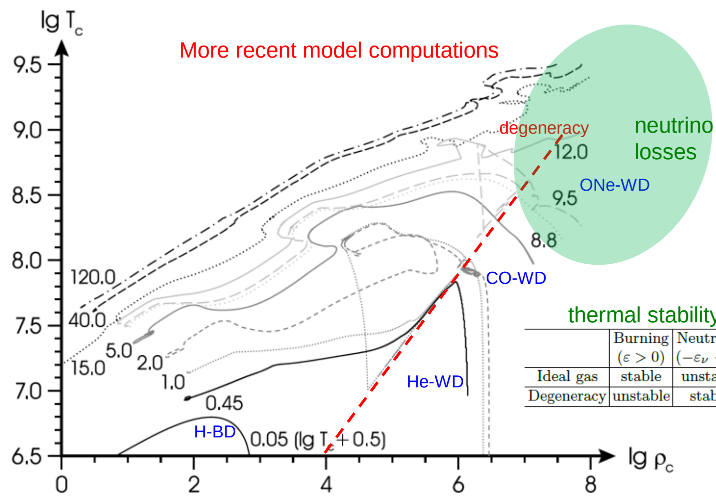
critical masses for ignition in degenerate core:

$M'_c > 0.48\ M_\odot$ ignition in degenerate He core

$M'_c > 1.40\ M_\odot$ ignition in degenerate C-O core

Evolution (1 – 9 $M_\odot$) of degenerate He & C-O core first lead to strong cooling followed by T↑& expansion until stable burning is reached. Core structure independent of envelope → evolution of central values converges for stars of different *M* but with same M_c.

Later phases of core evolution



thermal stability

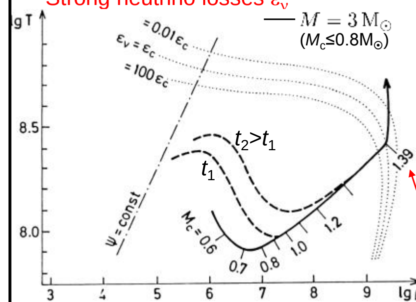
	Burning ($\varepsilon > 0$)	Neutrinos ($-\varepsilon_\nu < 0$)
Ideal gas	stable	unstable
Degeneracy	unstable	stable

we see that the models with $M = 0.05$, 0.45, and $8.8\,M_\odot$ just miss the ignition of H, He, and C, respectively.

Later phases of core evolution

(degenerate CO core : C-flash)

Strong neutrino losses ε_ν



If (He) shell source were extinguished, (degenerate) core would just cool down with ρ_c=constant to the white-dwarf state (vertical line in previous figure).

Continuous burning of shell source increases M_c and also $\rho_c \sim M_c^2$ (and T in shell [homology]), i.e. evolution continues to the right in the HR-D; core contraction due to this effect releases ε_g and heats (via heat transport, e.g. conduction) core.

HOWEVER: strong neutrino losses ε_ν cool central regions of degenerate core; max(T) off centre.

When growing $M_c \approx 1.4\,M_\odot$, neutrino losses $\varepsilon_\nu = \varepsilon_c$; and pycnonuclear C burning ε_c starts dominating over neutrino losses → **C-flash**! and C burning starts thermal runaway (if this happens at centre it could disrupt the whole star – **supernova** outburst **without** a neutron star as a remnant (type Ia).

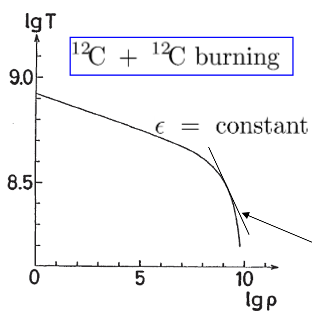
Nuclear energy production

Electron screening

Screening factor f important for large ρ & low T

Consider shielded reaction rate $f\langle\sigma v\rangle = f_0\langle\sigma v\rangle_0 \left(\frac{\varrho}{\varrho_0}\right)^{\lambda} \left(\frac{T}{T_0}\right)^{n}$

In the neighbourhood of ρ_0 and T_0: $n = \frac{\eta}{2} - \frac{2}{3} - \frac{E_D}{kT}$; $\lambda = 1 + \frac{1}{3}\frac{E_D}{kT}$



for ρ >> and T << $\longrightarrow \lambda \gg$ & $n \ll$

$\longrightarrow$ "pycnonuclear reactions"

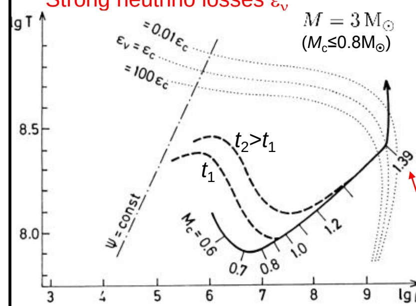
$\longrightarrow$ $\epsilon = \epsilon(\rho)$ and not $\epsilon = \epsilon(T)$

slope = -1, where $\lambda = n$

Later phases of core evolution

(degenerate CO core : C-flash)

Strong neutrino losses ε_ν



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- CO core is ignited if $M_c \approx 1.4\,M_\odot$ (1.1 – 1.5 $M_\odot$ for ZAMS with M=9,…,11.5 $M_\odot$).
- Stars with M=1.4 – 9.0 $M_\odot$ develop degenerate CO cores.
- For M > 9$M_\odot$ C-O core does not become degenerate during contraction after central He burning; T_c↑ and central C-burning starts. Here ε_ν >> carrying away most of energy.
- Massive stars go all the way through the nuclear burnings until Fe. Then core becomes unstable & collapses→ e^- capture →neutron star, and envelope blown away by supernova explosion.

Neutrinos

Additional to neutrino production within nuclear burning stages there are nuclear reactions that are not connected to nuclear burning, e.g.

(a) Electron capture (neutronization, extreme high densities):

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

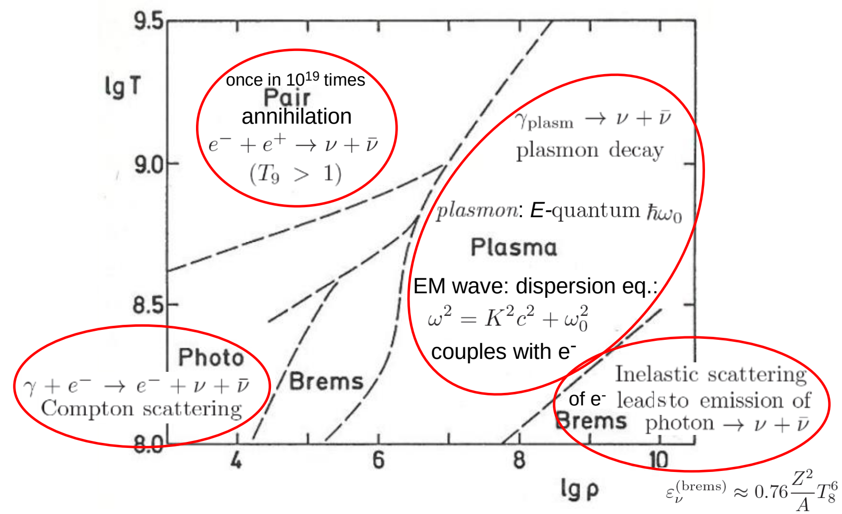
(b) Urca process:

$$(Z, A) + e^- \to (Z-1, A) + \nu \ ,$$
$$(Z-1, A) \to (Z, A) + e^- + \bar{\nu} \ .$$

Nuclear energy production

Neutrinos

other processes without nuclear reactions



Nuclear energy production

Neutrinos

other processes without nuclear reactions