

Later phases of core evolution (of sufficiently massive stars)

nuclear burning

core heating

exhaustion of fuel

core contraction

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

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 ⁵⁶Fe 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 ($T_c \sim M_c$).

From homology (homologous contraction $\dot{r}/r = \dot{R}/R \rightarrow d_m(\dot{r}/r) = 0 \rightarrow d_c(r^{-1}d_m r) = 0$) we obtain:

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

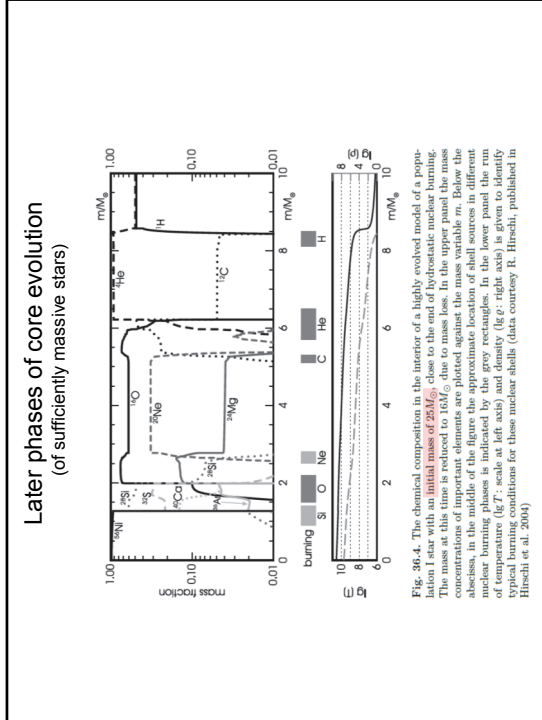
depends critically on EOS > 0 for contraction

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

degeneracy parameter $\psi = \psi(\rho_c/T_c^{3/2}) \uparrow$ [$\psi = \text{constant for } dT/T = (2/3)(d\rho/\rho)$]

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.



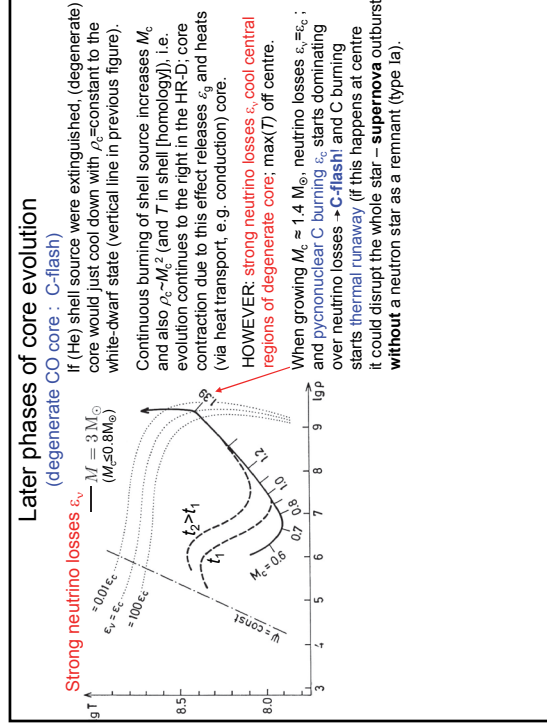
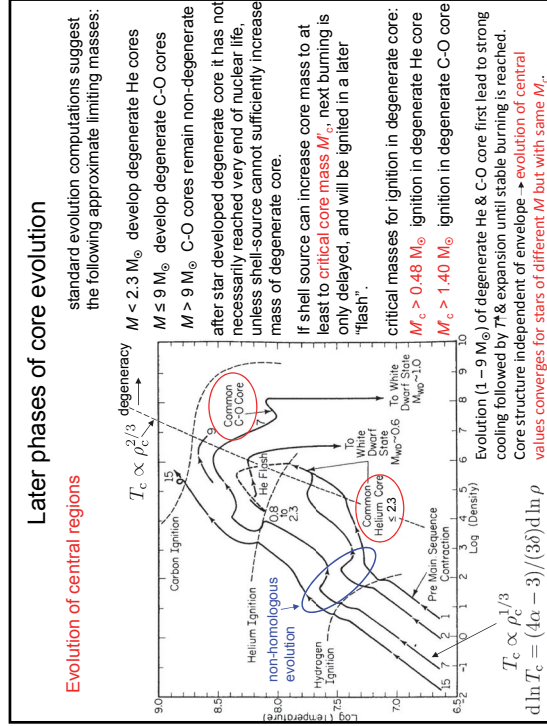
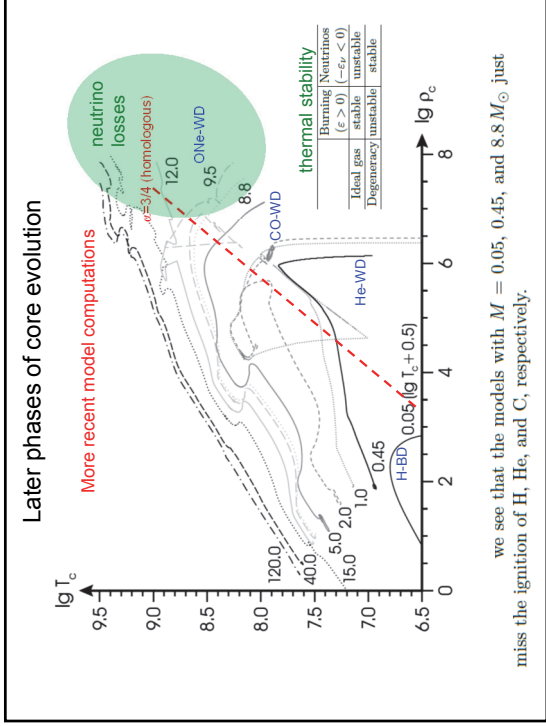
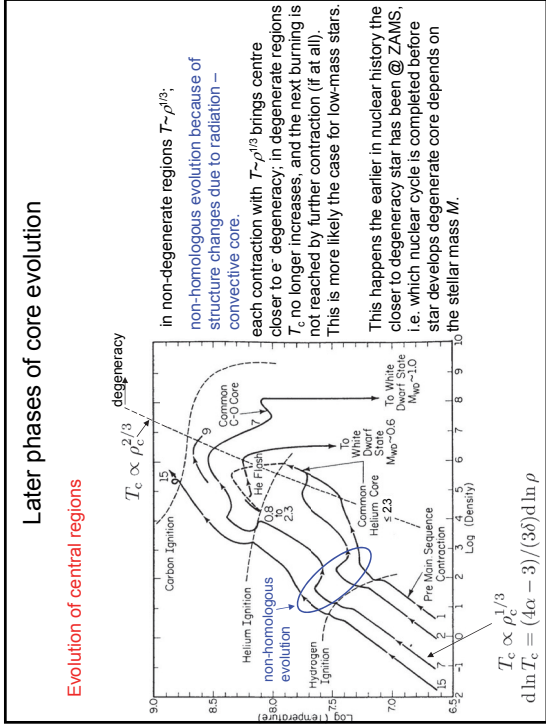
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Typical timescales for nuclear burning

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	9.97×10^5	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}

$t_{\text{nuc}} \lesssim t_{\text{KH}}$ → core changes no longer reflected at surface.

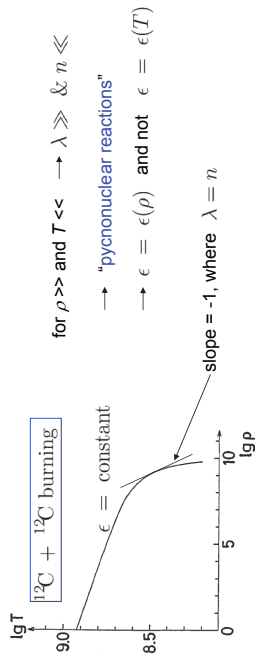


Nuclear energy production Electron screening

Screening factor f : important for large ρ & low T

Consider shielded reaction rate $f(\sigma\nu) = f_0(\sigma\nu)_0 \left(\frac{\rho}{\rho_0}\right)^\lambda \left(\frac{T}{T_0}\right)^n$

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



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):



(b) Urca process:



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 $\rho_c = \text{constant}$ 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_ν 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.

If growing $M_c \approx 1.4 M_\odot$, neutrino losses $\epsilon_\nu = \epsilon_c$; and pyncnonuclear C burning ϵ_c starts dominating over neutrino losses \rightarrow C-flash and C burning starts thermal runaway (if this happens at centre it could disrupt the whole star \rightarrow supernova outburst without a neutron star as a remnant (type Ia)).

- CO core is ignited if $M_c \approx 1.4 M_\odot$ (1.1 - 1.5 M_\odot for ZAMS with $M = 9, \dots, 11.5 M_\odot$).

- 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; $T_c \uparrow$ and central C-burning starts. Here $\epsilon_c \gg$ carrying away most of energy.

- Massive stars go all the way through the nuclear burnings until Fe. Then core becomes unstable & collapses \rightarrow e- capture \rightarrow neutron star, and envelope blown away by supernova explosion.

