PH20016 : Particles, Nuclei and Stars

Lecture 3 Stellar Evolution — Dr S R Davies

Helium Fusion

At higher temperatures still (> 10^8 K), then **helium burning** can occur, e.g. the **triple-alpha process**

$$^4He + {}^4He \Leftrightarrow {}^8Be$$
$$^8Be + {}^4He \Leftrightarrow {}^{12}C^* \qquad \text{(excited state of C)}$$

^8Be is unstable, but an equilibrium arises where some ^8Be takes part in the second step.

The mass of a ^8Be nucleus is slightly ***greater*** than the mass of two ^4He nuclei – the reaction requires the ***input*** of 91.8 keV of energy to proceed in the forward direction. If two ^4He nuclei approach each other with a combined kinetic energy close to 91.8 keV, there is an enhanced probability of them fusing into a ^8Be nucleus.

The second reaction also requires the input of energy to proceed in the forward direction (energy needed = 287.7 keV). Excited $^{12}C^*$ nuclei form only occasionally and will have a brief existence before breaking up through the reverse reaction.

Less than 0.1% of the $^{12}C^*$ decay: $^{12}C^* \rightarrow {}^{12}C + 2\gamma$ (7.65 MeV released)

Oxygen nuclei are also formed through: $^4He + {}^{12}C \rightarrow {}^{16}O + \gamma$

Light elements other than H, He, C and O are rare in the cores of stars, because such elements readily combine with protons to form ^4He.

The He burning processes are very sensitive to temperature and density.

p-p Chain	CNO Cycle	Triple-Alpha Process
E gen. rate $\propto T^4$	E gen. rate $\propto T^{20}$	E gen. rate $\propto T^{30}$

Advanced Burning

For more massive stars, fusion reactions will evolve beyond helium burning. Stages of carbon, neon, oxygen, magnesium and silicon burning can occur.

Burning Stage	Major Products	Temperature	Stellar Mass
Helium	C, O	2×10^8 K	1 $M_\odot$
Carbon	O, Ne, Na, Mg	8×10^8 K	1.4 $M_\odot$
Neon	O, Mg	1.5×10^9 K	5 $M_\odot$
Oxygen	Mg, Si	2×10^9 K	10 $M_\odot$
Silicon	Elements near Fe	3×10^9 K	20 $M_\odot$

When the material rises above ~ 10^9 K,

Photodisintegration → nuclei broken up by high energy photons

→ nuclear material reduced to most stable forms

At core $T \sim 8 \times 10^8$ K, density of $\sim 3 \times 10^9$ kg.m^{-3}, then C burning can occur $\rightarrow$ Ne, Na, Mg

$$\text{e.g.} \qquad {}^{12}C + {}^{12}C \rightarrow {}^{20}Ne + {}^{4}He$$
$$\rightarrow {}^{24}Mg + \gamma$$

If the core reaches $\sim 10^9$ K, both neon burning and photodisintegration can take place.

$$\gamma + {}^{20}Ne \rightarrow {}^{16}O + {}^{4}He$$
$${}^{4}He + {}^{20}Ne \rightarrow {}^{24}Mg + \gamma$$

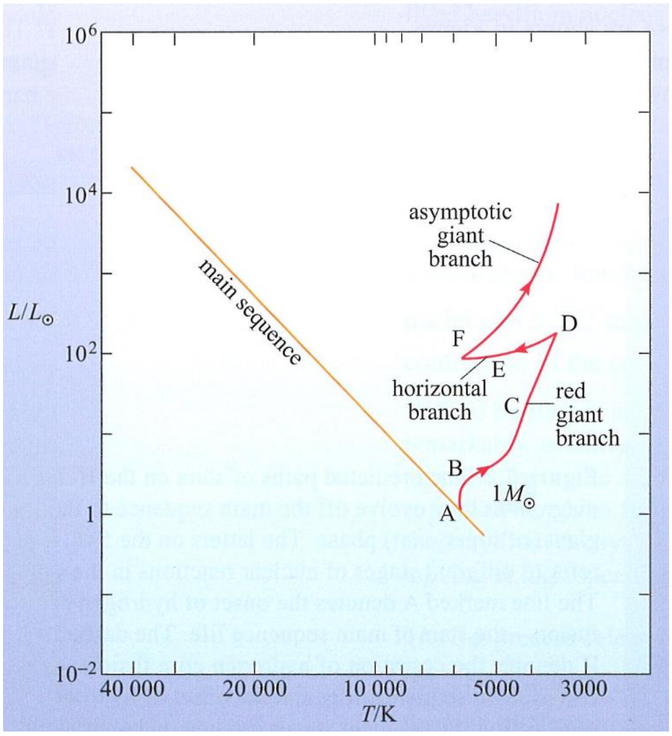
After neon burning, the core consists mainly of ${}^{16}O$ and ${}^{24}Mg$.

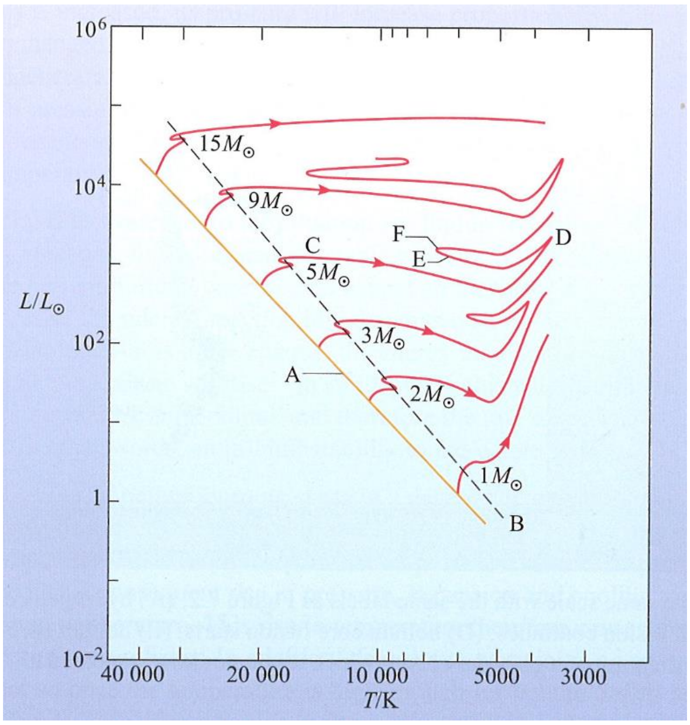
Si burning can occur at $\sim 3 \times 10^9$ K. Competing photodisintegration and capture reactions
$\rightarrow$ produces ${}^{32}S$, ${}^{36}Ar$, ${}^{40}Ca$ etc. up to ${}^{56}Ni$.

Photodisintegration processes favour the formation of nuclei near A = 56

Overview of Stellar Evolution

Post-main sequence evolution is very similar for all stars in the initial stages:





A Onset of hydrogen core fusion (start of main sequence)

B End of hydrogen core fusion (end of main sequence)

C Ongoing hydrogen shell fusion

D Onset of helium core fusion

E Ongoing helium core fusion

F Onset of helium shell fusion

A-B. H fusion in core via p-p chain / CNO cycle. Lasts ~ 10^{10} yrs (1 $M_\odot$), 10^{8} yrs (5 $M_\odot$)

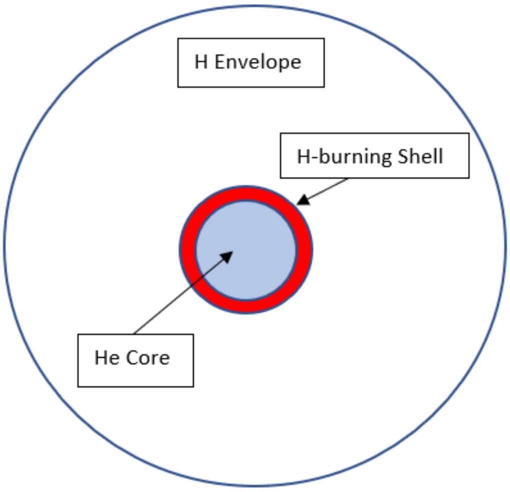
- core gradually enriched in He

C. Eventually the core hydrogen (~ 0.1 $M_\odot$) is exhausted and H fusion slows down / stops

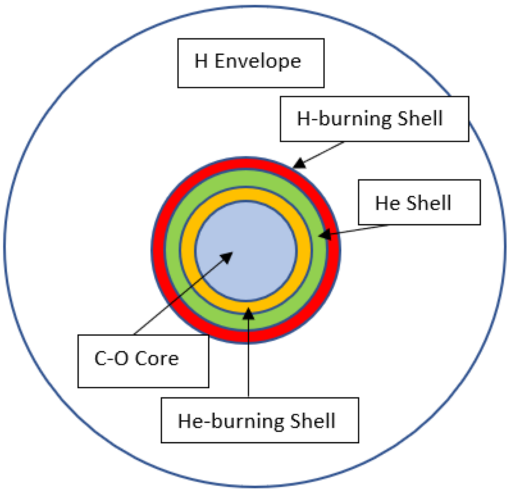
- central P cannot resist collapse; core contracts and gets hotter ($E_{GR} \rightarrow E_{KE}$)
- H burning starts in a shell surrounding the (primarily) He core
- Outer layers of star pushed outwards $\rightarrow$ expand and cool

D. The core temperature reaches ~ 10^{8} K

- triple-alpha process starts at star's centre, fusing He into C
  ... for 1 $M_\odot$ star, core is degenerate, for 5 $M_\odot$ star, core is non-degenerate (degenerate matter will be discussed later)
- Convection zone reaches down towards core ... dredges up C, N to surface



Hydrogen-Shell Burning



Helium-Shell Burning

The later stages of stellar evolution depend greatly upon the stellar mass:

<u>1 $M_\odot$ star</u>

D. Large rise in T for modest rise in P
$\rightarrow$ He flash ... rapid rise in E generation

E. Star stabilises
hot core causes outlying shell to expand
E generation rate in shell diminishes
outer envelope contracts $\rightarrow R\downarrow \quad T\uparrow$

F. He fusion in core ends; starts in shell.

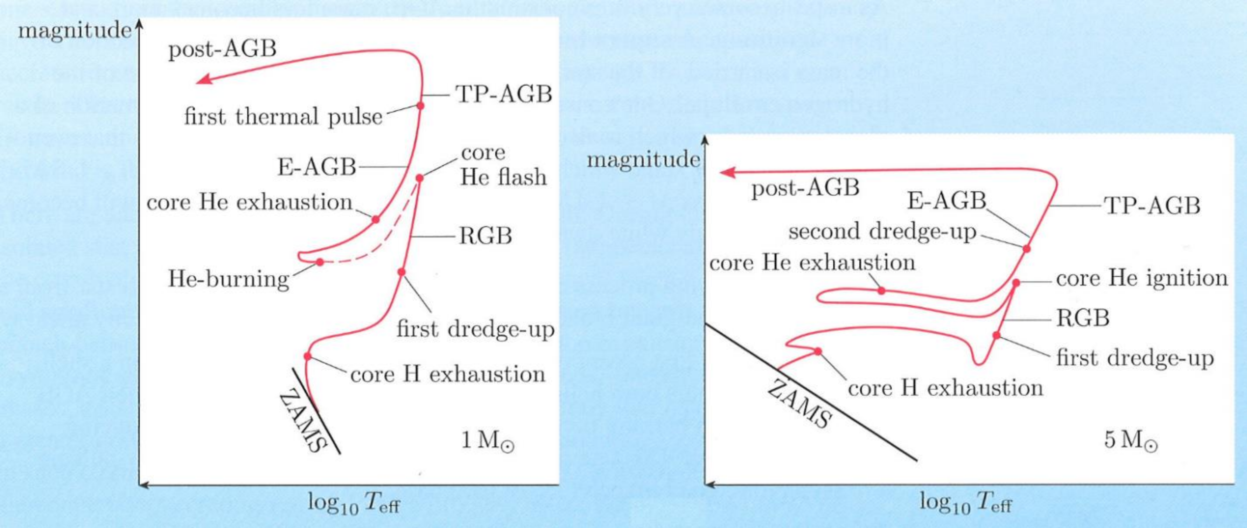
<u>5 $M_\odot$ star</u>

D. Large rise in T, large rise in P; core expands, He fusion onset more controlled

E. Star stabilises
core and shell expand, shell fusion falls
outer envelope contracts $\rightarrow R\downarrow \quad T\uparrow$
moves back towards MS $\rightarrow$ ***blue giant***

F. He fusion in core finished. Core contracts and heats up. He fusion starts in shell.

The carbon-oxygen core is surrounded by a helium-burning shell, outside of which is a hydrogen-burning shell. The latter is now further from the core and, once again, causes the outer hydrogen layers to expand $\rightarrow$ the star moves up the ***asymptotic giant branch*** (early, or E-AGB at first)



He fusion in shell very sensitive to T, ρ .

Thermal instabilities in the helium shell drive ***thermal pulses*** (TP-AGB phase)

Star pulses: expands $\rightarrow$ cools $\rightarrow$ contracts $\rightarrow$ heats … He fusion diminishes/re-ignites.

1 $M_\odot$ star

* Pulsations throw off outer layers to form a ***planetary nebula.***
  Core temp. insufficient for C fusion
* Hot, dense C core becomes a ***white dwarf***
* White dwarf slowly cools $\rightarrow$ ***black dwarf***

5 $M_\odot$ star

* Star pulsates ... ***Cepheid variable***
  Period of variability related to luminosity
* C fusion and other advanced burning stages occur in sequence, producing elements up to Mg, Si, (Fe); star has become a ***supergiant***
* Outer layers dispersed by strong stellar wind
  Star becomes a ***high-mass white dwarf***

Degenerate Electron Gas

The central core of massive stars (and white dwarfs) consists of material that is so dense, it no longer behaves like an ordinary (ideal) gas. It becomes so tightly packed that the motions of the electrons are subject to limitations imposed by the proximity of other electrons.

When their separation becomes comparable to their de Broglie wavelengths:

Pauli Excl. Pr. → prohibits overlapping of e^- having same E

In a very dense plasma:

... only two e^-, opp. spin, can have given E in a given vol.
→ e^- forced into states with specific E levels
→ deg. e^- gas

The nuclei remain fixed relative to each other → like a crystal lattice

In a degenerate electron gas, the pressure is governed by an equation of state of the form:

$$P_{NR} = K_{NR}\, n_e^{5/3}$$ for non-relativistic case

$$P_{UR} = K_{UR}\, n_e^{4/3}$$ for ultra-relativistic case

where non-relativistic means K.E. << rest mass energy

→ pressure is independent of T ... depends only upon n_e

→ increase in P does <u>not</u> lead to an increase in T

Electrons will become degenerate when $\lambda_{DB} \simeq \frac{h}{(3 m_e k T_c)^{1/2}}$

Note that the de Broglie wavelength for an electron is ≈ 40 times longer than for a nucleon (proton or neutron).

An equivalent condition for degeneracy is when the number density of particles, *n*, is higher than the number of available quantum states (quantum concentration) which, under non-relativistic conditions can be expressed as

$$n \gg n_{QNR} = \left(\frac{2\pi m k T}{h^2}\right)^{3/2}$$

In the core of the Sun, the number density of electrons is less than the quantum concentration, but only by about a factor of 2 – the core of the Sun behaves as a classical gas, but it is not far from becoming a degenerate electron gas.

As the He core grows, through H-fusion, the number density of electrons will eventually exceed the quantum concentration when the Sun becomes a red giant (at $T \approx 10^8$ K).

When He-fusion begins, an enormous amount of energy is released into the core. If the core were a classical gas, it would undergo a large expansion, reducing the density and temperature and hence the reaction rate. For a DEG, the decoupling of temperature from pressure means that increasing the temperature of the particles will not necessarily drive an expansion.

The core will be part-classical gas, part-degenerate gas. Electron-degeneracy pressure dominates the total pressure. There will be some expansion, but not enough (initially) to compensate for the temperature increase. This results in a very rapid rise in the fusion reaction rate – the ***helium flash***, that was mentioned above. The energy generation in the core increases by many orders of magnitude, but this ultimately goes into driving expansion of the core – it does not result in the surface brightness of the star increasing. The core density eventually drops sufficiently so that the electrons are no longer degenerate and the helium fusion continues in a more controlled way.

More massive stars have a lower density for a given temperature. Stars with $M > 2.5\ M_\odot$ start helium fusion ***before*** they reach the density required for electron degeneracy. The helium fusion process is more controlled in such stars.

White Dwarfs

- Sun-like star passes through H-burning, then He burning
  → forms C-O core, surrounded by He and H
- Outer envelope forms planetary nebula
  → core emerges as W.D.
- W.D.s can have mass ~ $0.2 M_\odot$ to $1.4 M_\odot$
- $1 M_\odot$ main seq. star might form W.D. of ~ $0.6 M_\odot$; mostly C, O
- Massive W.D. formed from massive star; up to Fe/Ni
- Core supported by deg. electron pressure (not ideal gas)
  → more massive W.D. has smaller R
  → pressure increases with density (mass), not T