Evolution From Main-Sequence Phase

- Stars of different masses evolve from main-sequence (m - s) to red giant (r - g) phase very differently, because of influence of extent of convective or radiative cores

M/M_{SUN}	M_{CC}/M	M_{CE}/M
15	0.38	0.00
3	0.17	0.00
0.5	0.01	0.42

M_{CC} = mass of convective core
M_{CE} = mass of convective envelope

Evolution of a 5 M_{Sun} star

1) m-s star:
convective core ~ 21% of mass;
H → He fusion by CNO cycle in inner 7% of mass

2) H depletion in core → overall contraction; convective core now half its original mass

STELLAR EVOLUTION

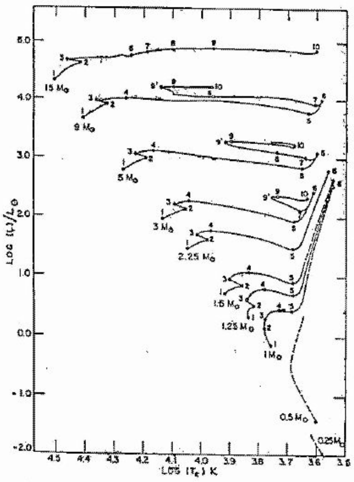


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_{\odot}) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths are estimates.

TABLE III

STELLAR LIFETIMES (yr)*

Mass ($M_{\odot}$) \ Interval (i–j)	(1–2)	(2–3)	(3–4)	(4–5)	(5–6)
15	1.010 (7)	2.270 (5)		7.55 (4)	
9	2.144 (7)	6.053 (5)	9.113 (4)	1.477 (5)	6.552 (4)
5	6.547 (7)	2.173 (6)	1.372 (6)	7.532 (5)	4.857 (5)
3	2.212 (8)	1.042 (7)	1.033 (7)	4.505 (6)	4.238 (6)
2.25	4.802 (8)	1.647 (7)	3.696 (7)	1.310 (7)	3.829 (7)
1.5	1.553 (9)	8.10 (7)	3.490 (8)	1.049 (8)	≥2 (8)
1.25	2.803 (9)	1.824 (8)	1.045 (9)	1.463 (8)	≥4 (8)
1.0	7 (9)	2 (9)	1.20 (9)	1.57 (8)	≥1 (9)

* Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

TABLE IV

STELLAR LIFETIMES (yr)*

Mass ($M_{\odot}$) \ Interval (i–j)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
9	4.90 (5)	9.50 (4)	3.28 (6)	1.55 (5)
5	6.05 (6)	1.02 (6)	9.00 (6)	9.30 (5)
3	2.51 (7)	4.08 (7)		6.00 (6)

* Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

3) end of m-s phase: point of central H exhaustion; establishment of H - burning shell source.

Isothermal He core soon has mass > S - C limit

→ rapid collapse of core

→ release of gravitational p.e. which heats inner shell

→ Shell source initially quite thick but it narrows as it burns outwards.

(3 - 5) Core collapse + rapid burning from shell source forces outer layer to expand quickly. T_c too low for He fusion.

(5) Deep outer convection zone - 54% of mass of star - ensures efficient energy transport outwards. Energy increase → luminosity increase and near vertical movement in HR diagram. H shell source now very thin ~ 1% of mass.

(6) RED GIANT TIP - point of central He ignition at $T_c \sim 10^8$ K. He → C by "triple - α" process

$$
\begin{array}{lllllll}
{}^4_2\mathrm{He} & + & {}^4_2\mathrm{He} & \rightarrow & {}^8_4\mathrm{Be} & + & \gamma \quad -95\ \mathrm{keV} \\
{}^8_4\mathrm{Be} & + & {}^4_2\mathrm{He} & \rightarrow & {}^{12}_6\mathrm{C} & + & \gamma \quad 7.4\ \mathrm{MeV}
\end{array}
$$

Energy release rate $\varepsilon \propto T^{38}$. He → C in new convective core, only really effective in inner 1%. - hence only lasts ~ 10% of m-s lifetime.

(8) Convective core smaller

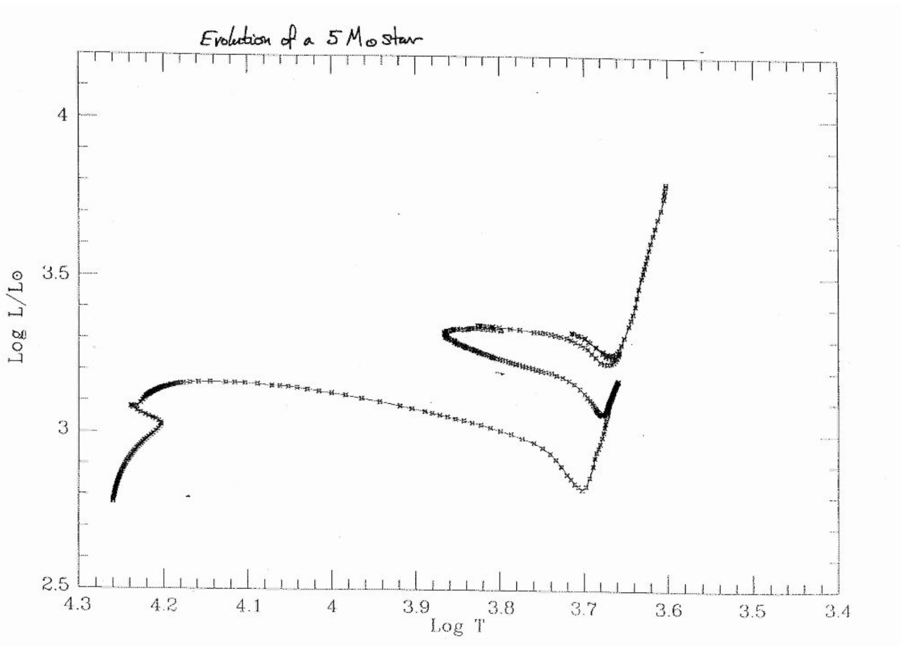
(9) No He left; isothermal C core plus He → C shell source established. H → He finished.

(10) Deep outer convection zone - 80% of mass - contracting C core *may* reach sufficiently high temp for next stage.

SUPERGIANT STAGE: nuclear reactions

$$^{12}C + ^{12}C \rightarrow ^{24}Mg + \gamma$$
$$^{12}C + ^{12}C \rightarrow ^{23}Na + p$$
$$^{12}C + ^{12}C \rightarrow ^{20}Ne + ^{4}He$$

Beyond this point?
Most likely white dwarf ~ $1M_{Sun}$ as end state



Evolution of a 1 M_{Sun} star

1) m-s star; H → He fusion by pp chain; isothermal, radiative He core builds up in mass only gradually.

2) end of core H burning; contracting He core releases grav. p.e. and accelerates H fusion in new shell source.

3) Shell source causes outer layers to expand and star moves through subgiant to red giant stage.

Isothermal He core contracts steadily before S-C limit is reached.

Hence steady progression from m-s phase through subgiant region to r-g phase

(5-6) Red giant stage with 1 M_{Sun} star having

$L \sim 1000\ L_{Sun}$,

$R \sim 100\ R_{Sun}$,

$T \sim 3000$ K.

Core $T \sim 50 \times 10^6$ K,

radius ~ few Earth radii

- matter in core so dense that it becomes electron degenerate. This introduces an additional gas pressure dependent only on density, not on temperature.

Aside on degenerate gas:

Heisenberg's uncertainty principle: $\Delta x \Delta p > \hbar$

At high ρ, particles closely packed

→ Δx small → Δp large

→ particles have higher momentum than predicted due to kinetic theory

→ higher pressure than classical gas.

Momentum essentially determined by **Pauli's exclusion principle** (∴ indep of temperature).

Electron-degenerate pressure $\propto \rho^{5/3}$ (non-relativistic)

or $\propto \rho^{4/3}$ (relativistic).

- There are two reasons for the end of the expansion towards the red-giant stage:

1) core becomes hot enough for He → C burning, as in more massive star OR

2) electron - degeneracy pressure stops further contraction of core

Evolution beyond the red-giant stage: the helium flash

- He → C by 3α process. But since core is electron-degenerate, the pressure is not a function of temp → the increase in temp from fusion reactions does not give an increase in pressure as in a perfect gas ∴ core does not expand.

- Energy generated at $\varepsilon \propto T^{38}$ initially goes into "lifting" degeneracy ... for a few secs, core $L \sim 10^{11} L_{Sun}$ until degeneracy removed at $T \sim 3.5 \times 10^8$ K.

- The k.e. ↑ , core expands, T ↓ , reaction throttled back.

- Star returns to steady state, radius + luminosity decrease somewhat.

  Star then occupies the short blueward extension of the red giant region called the HORIZONTAL BRANCH (by analogy with that section of C-M diagrams of globular clusters).

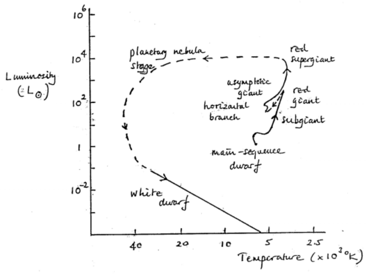
- End of core He → C fusion, isothermal C core, He → C shell source.

  As at end of m-s phase, the same physical reasons make the star expand again to the r-g region along the ASYMPTOTIC GIANT BRANCH as an AGB star.

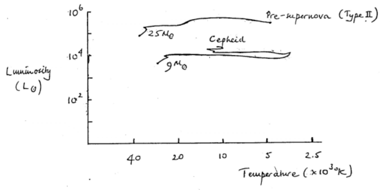
- The He → C shell sources in AGB stars can be unstable to small-scale perturbations in temperature and pressure.
- Results in He flash episodes in the shell region. Can be sufficiently violent to cause ejection of the outer layers of distended giant envelope in one or more episodes - the PLANETARY NEBULA phase.
- Central core of the 1 M_{Sun} star has mass ~ 0.55 - 0.60 M_{Sun} and is exposed after ejection of the giant envelope. Core does not reach high enough temperature for C fusion and becomes electron-degenerate which prevents contraction.

- Star passes through the SUBDWARF O STAR phase quite quickly (~75,000 years) en route to the WHITE DWARF phase. Star composed mostly of C (+O) with thin layer of He and maybe H on top.
- No energy source left, white dwarf cools down slowly by radiation at constant radius (electron-degenerate pressure support) over ~ n x 10^9 years.

Stellar Evolution



Evolution of a low-mass ($1 M_\odot$) star from the main-sequence stage to a white dwarf.



Evolution of higher mass stars from the main-sequence stage

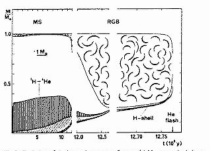


Fig. 5. Evolution of the internal structure of stars of $1 M_\odot$ up to the helium flash. Cloudy regions represent convective zones, bold vertically hatched regions are zones where the nuclear energy rates are between 1 and 10 erg $g^{-1} s^{-1}$. Diagonals indicate regions of rates > 10 erg $g^{-1} s^{-1}$. The observable status of the star is indicated: MS means main sequence and RGB red giant branch

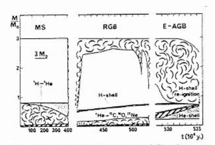


Fig. 6. Same as Fig. 5 for the $3 M_\odot$ model up to the end of the early asymptotic giant branch phase (E-AGB). Bold diagonals indicate regions where the nuclear energy rates are larger than 10^3 erg $g^{-1} s^{-1}$. The vertically hatched regions are zones of variable hydrogen and helium contents and the horizontally hatched zones represent areas of variable ^{12}C, ^{16}O, and ^{22}Ne contents

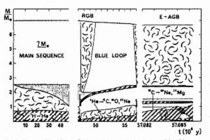


Fig. 8. Same as Fig. 6 for the $7 M_\odot$ model up to the beginning of the C-burning phase

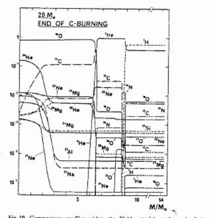


Fig. 10. Composition profiles within the $20 M_\odot$ model at the end of the C-burning phase, when $X(^{12}C)$ at the centre = 0.002417. Abscissa, the lagrangian mass coordinate; ordinate, the mass fraction

STELLAR EVOLUTION

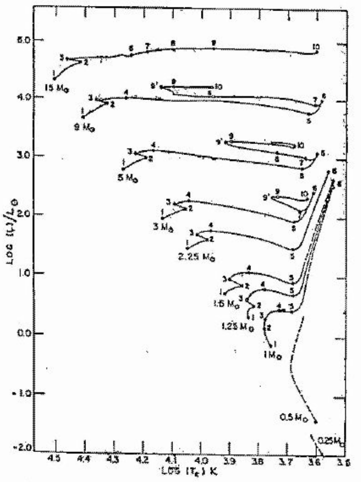


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_{\odot}) = 15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths are estimates.

TABLE III

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TABLE IV

STELLAR LIFETIMES (yr)*

Mass ($M_{\odot}$) \ Interval (i–j)	(6–7)	(7–8)	(8–9)	(9–10)
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