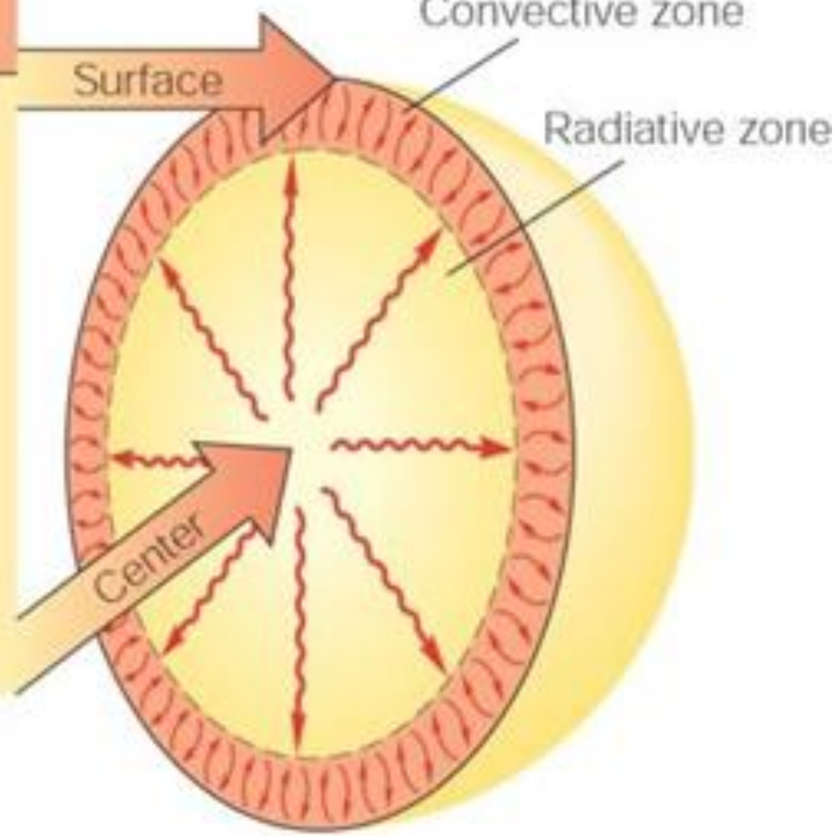
The Internal Structure of the Sun

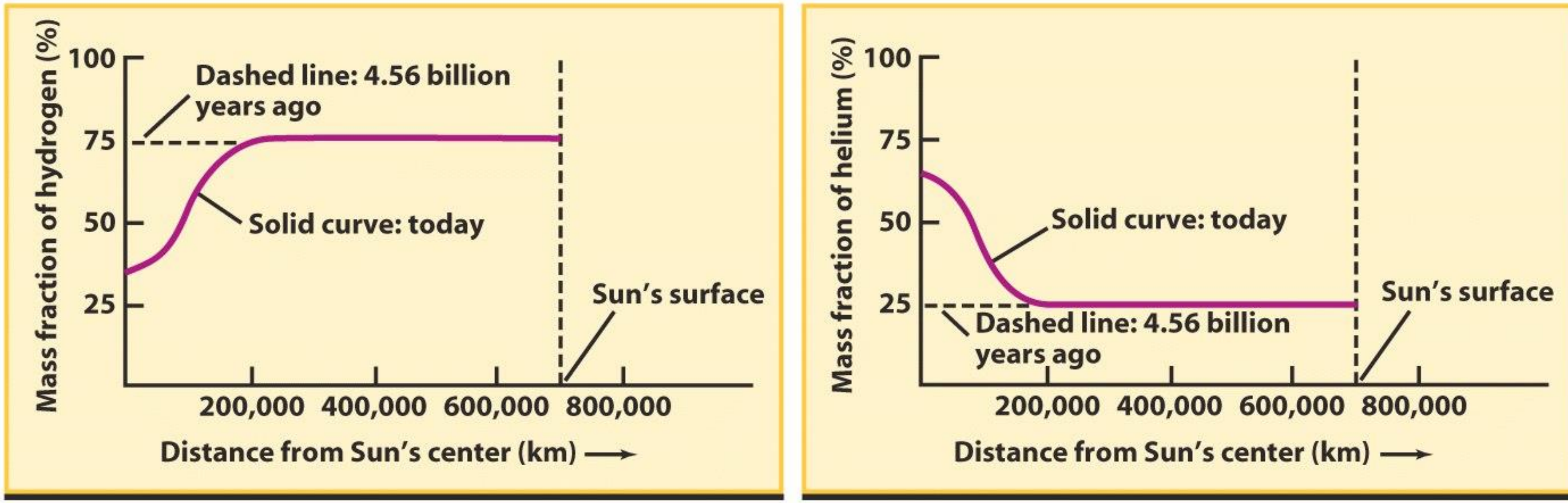
$R/R_\odot$	T (10^6 K)	Density (g/cm^3)	$M/M_\odot$	$L/L_\odot$
1.00	0.006	0.00	1.00	1.00
0.90	0.60	0.009	0.999	1.00
0.80	1.2	0.035	0.996	1.00
0.70	2.3	0.12	0.990	1.00
0.60	3.1	0.40	0.97	1.00
0.50	4.9	1.3	0.92	1.00
0.40	5.1	4.1	0.82	1.00
0.30	6.9	13.	0.63	0.99
0.20	9.3	36.	0.34	0.91
0.10	13.1	89.	0.073	0.40
0.00	15.7	150.	0.000	0.00



The Sun: 4.5 billion years old

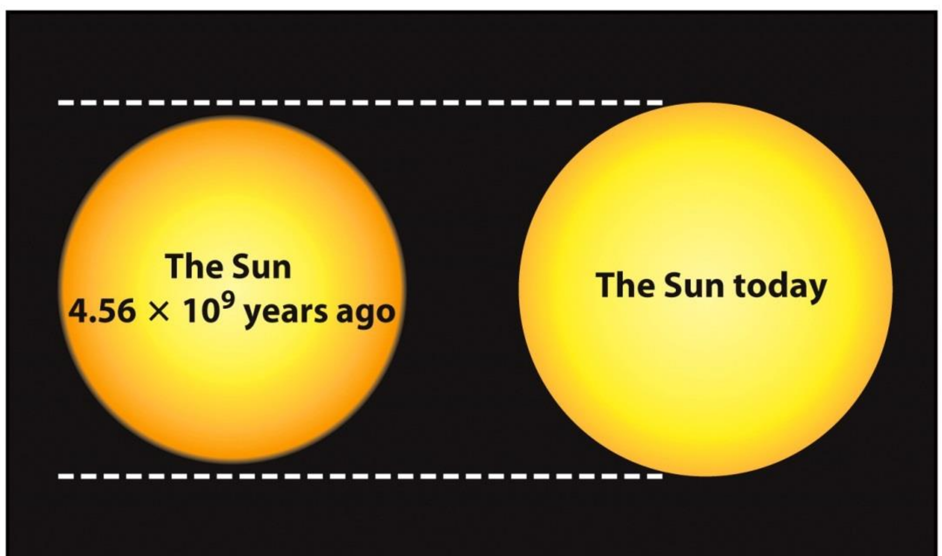
- The Sun has been a main-sequence star for 4.5 billion years, and at the core
  1. Hydrogen depleted by about 35%
  2. Helium amount increased
  3. Become 40% more luminous
  4. Has grown in radius by 6%
- The Sun should remain on the main sequence for another 7 billion years
- The Sun or 1 $M_{\odot}$ star has a main sequence lifetime of 12 billion years

The Sun: 4.5 billion years old

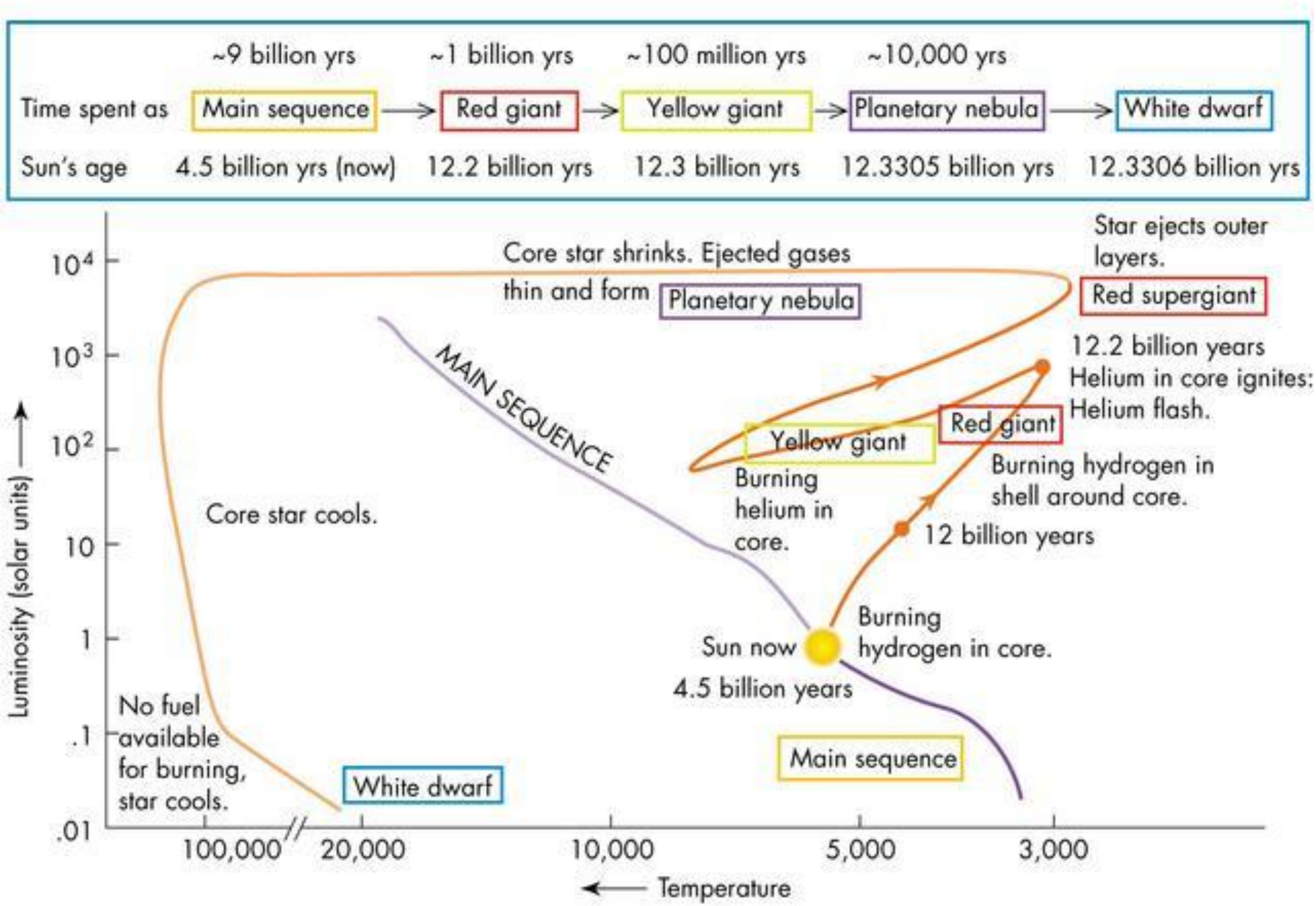


(a) Hydrogen in the Sun's interior

(b) Helium in the Sun's interior



The Evolution of the Sun



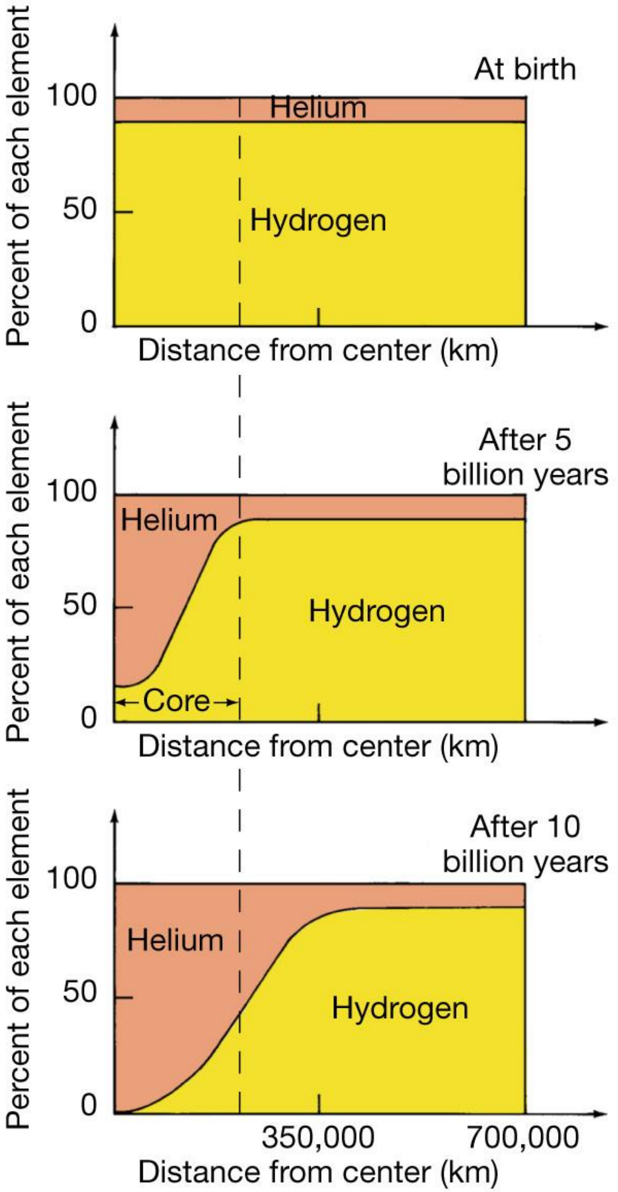
Change of chemical composition

Asplund et al., 2009, Annual Review of Astronomy & Astrophysics, 47, 481

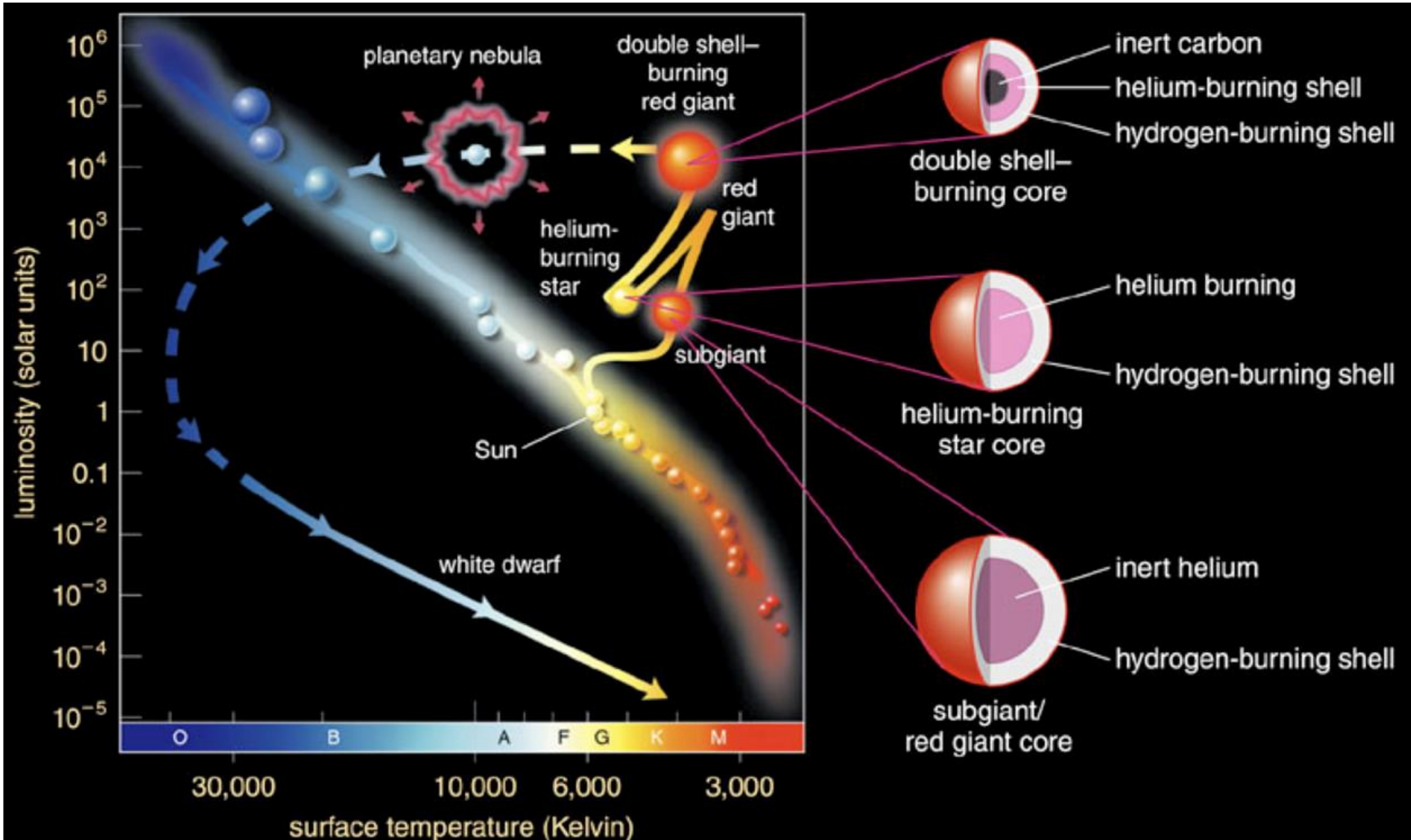
Table 4: The mass fractions of hydrogen (X), helium (Y) and metals (Z) for a number of widely-used compilations of the solar chemical composition.

Source	X	Y	Z	Z/X
Present-day photosphere:				
Anders & Grevesse (1989)[a]	0.7314	0.2485	0.0201	0.0274
Grevesse & Noels (1993)[a]	0.7336	0.2485	0.0179	0.0244
Grevesse & Sauval (1998)	0.7345	0.2485	0.0169	0.0231
Lodders (2003)	0.7491	0.2377	0.0133	0.0177
Asplund, Grevesse & Sauval (2005)	0.7392	0.2485	0.0122	0.0165
Lodders, Palme & Gail (2009)	0.7390	0.2469	0.0141	0.0191
Present work	0.7381	0.2485	0.0134	0.0181
Proto-solar:				
Anders & Grevesse (1989)	0.7096	0.2691	0.0213	0.0301
Grevesse & Noels (1993)	0.7112	0.2697	0.0190	0.0268
Grevesse & Sauval (1998)	0.7120	0.2701	0.0180	0.0253
Lodders (2003)	0.7111	0.2741	0.0149	0.0210
Asplund, Grevesse & Sauval (2005)	0.7166	0.2704	0.0130	0.0181
Lodders, Palme & Gail (2009)	0.7112	0.2735	0.0153	0.0215
Present work	0.7154	0.2703	0.0142	0.0199

[a] The He abundances given in Anders & Grevesse (1989) and Grevesse & Noels (1993) have here been replaced with the current best estimate from helioseismology (Sect. 3.9).



Next Phases



luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
planetary nebula
double shell–
burning
red giant
red
giant
helium-
burning
star
subgiant
Sun
white dwarf
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)
inert carbon
helium-burning shell
hydrogen-burning shell
double shell–
burning core
helium burning
hydrogen-burning shell
helium-burning
star core
inert helium
hydrogen-burning shell
subgiant/
red giant core

Subgiant Phase

- ***Core hydrogen fusion ceases*** when the hydrogen has been exhausted in the core of a main-sequence star
- This leaves a ***core*** of ***nearly pure helium***
- The ***core shrinks*** under self-gravitation due to the loss of hydrostatic equilibrium
- The ***core*** becomes ***hotter***
- ***Shell hydrogen fusion*** occurs just outside the core
- ***No fusion*** in the ***helium core***
- ***Subgiant Phase*** (***SGB***)

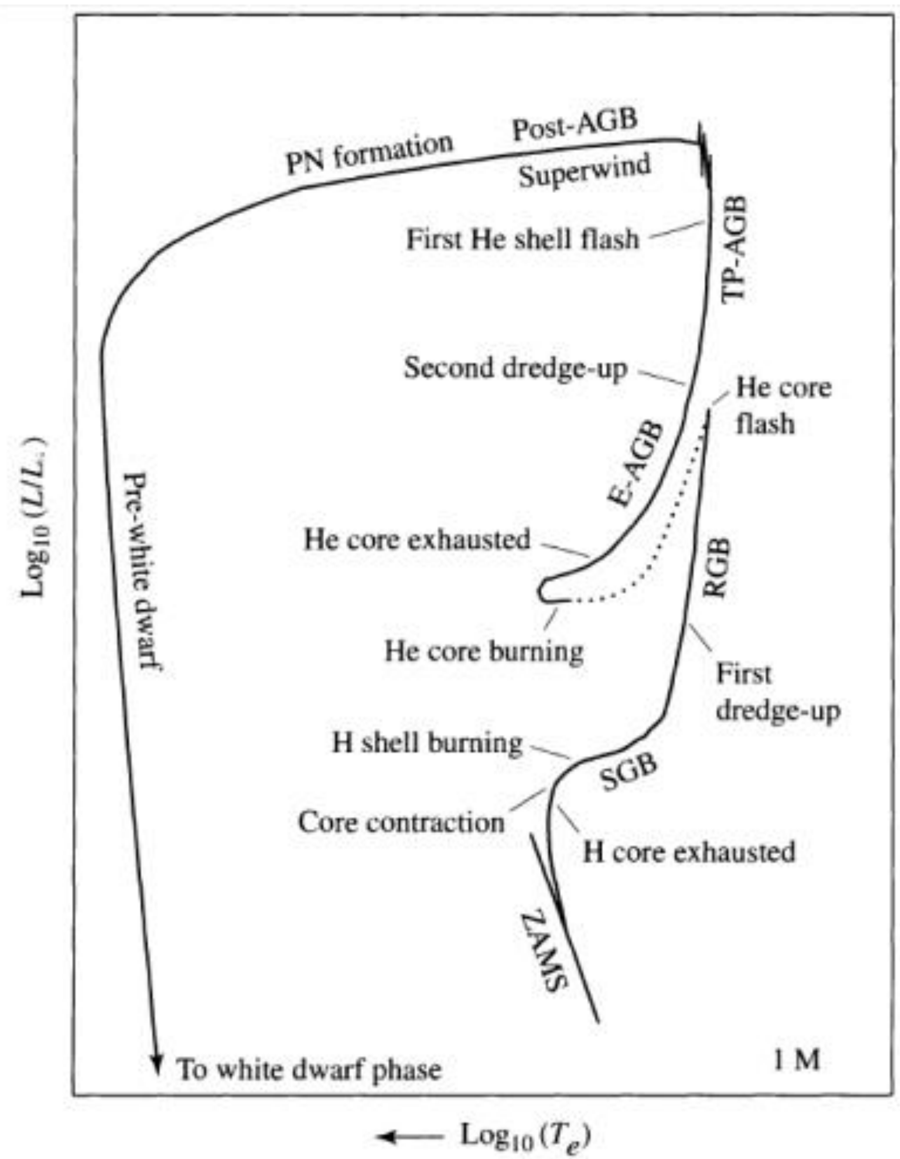
Red Giant Phase

- ***Shell hydrogen fusion*** works its way outward in the star and ***adds more helium*** into the ***core***
- ***Core becomes hotter***
- Shell hydrogen ***fusion*** occurs at a ***greater rate***
- ***Outer layers expands*** because of the increased energy flow
- At some point the core reaches the ***Schönberg-Chandrasekhar limit***

Schönberg-Chandrasekhar limit

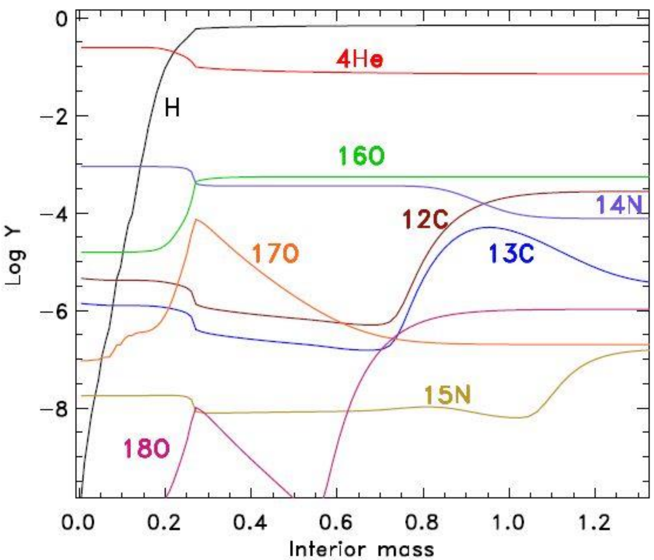
- The ***mass limit*** for the ***core*** which is capable of ***supporting*** the ***gravitational pressure*** of ***core and envelope***
- Core too massive => rapid contraction
- Release of a lot of gravitational potential energy
- Dumped into the envelope => heating up
- The Subgiant is now becoming a ***Red Giant*** (***Red Giant Branch, RGB***)

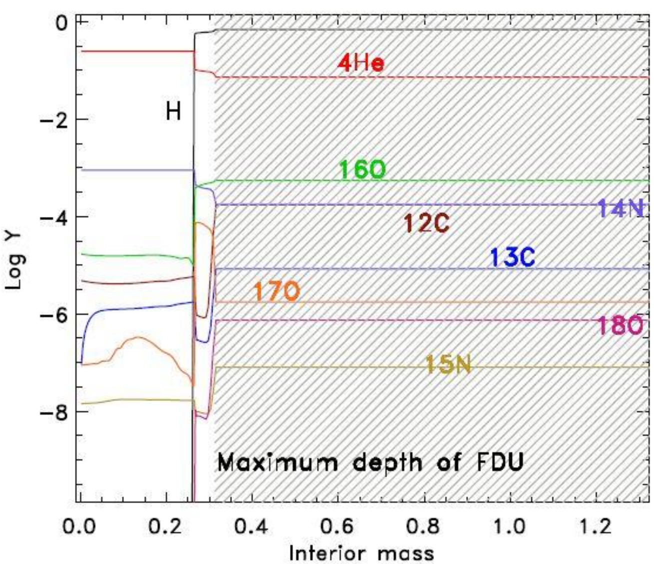
First dredge-up



As the outer atmosphere expands it becomes ***convective*** => ***Mixing***

First dredge-up



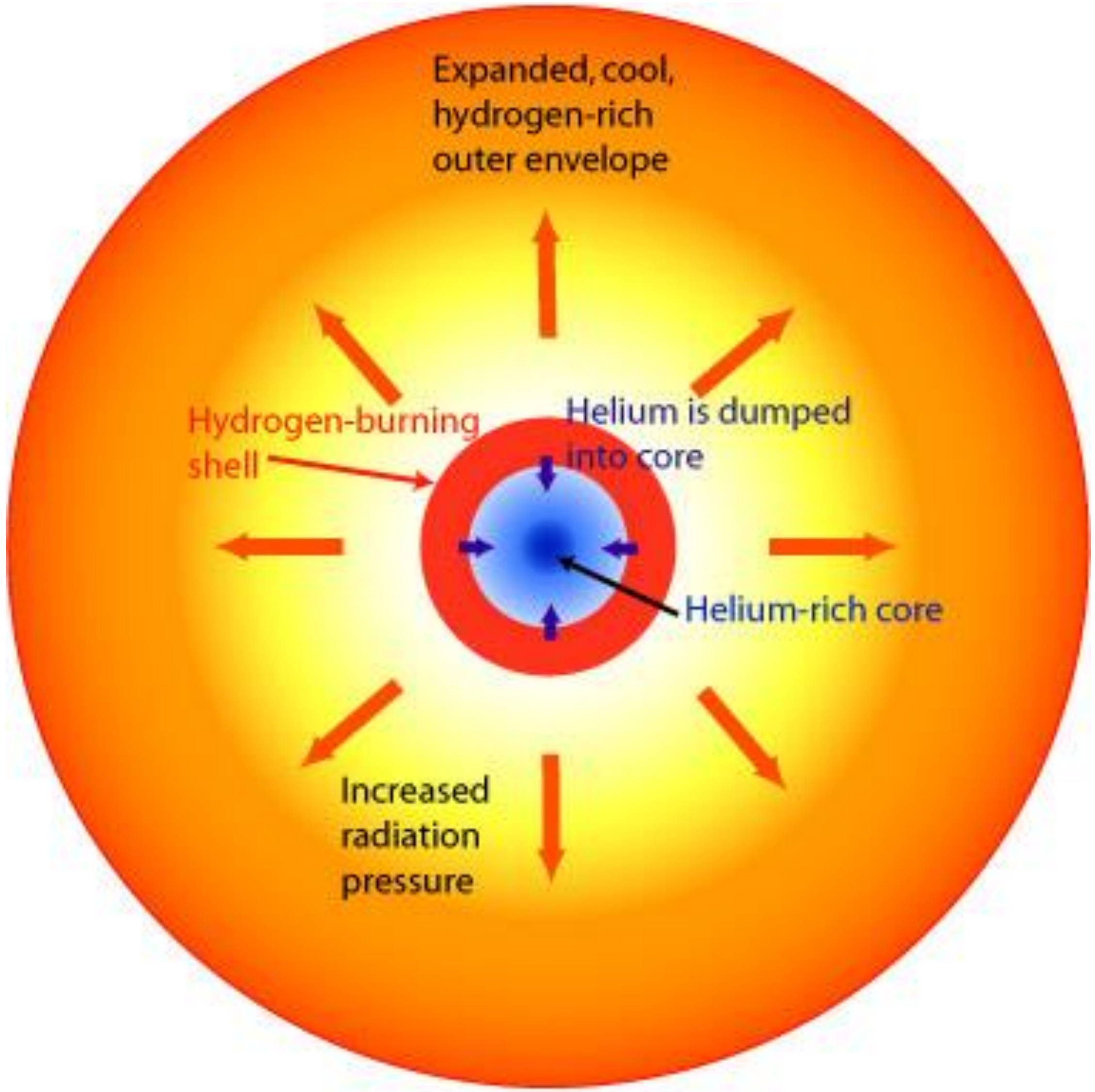


Composition depending on mass initial metallicity, and used theoretical model

1 $M_\odot$	Initial	After FDU
Y	0.280	0.3025
C/Z	0.1733	0.1530
N/Z	0.0531	0.0771
O/Z	0.4823	0.4822
^{3}He	8.4E-5	0.001368
^{12}C/^{13}C	90.0	29.8
^{16}O/^{17}O	2660	2610
^{16}O/^{18}O	500.1	526.9

1995astro.ph.12121B

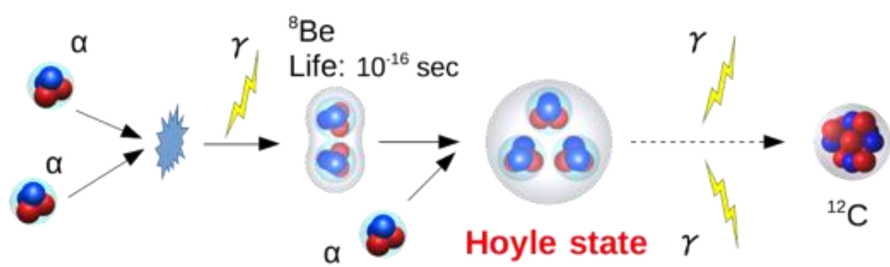
Red Giant Phase



Hydrogen Shell Burning on the Red Giant Branch

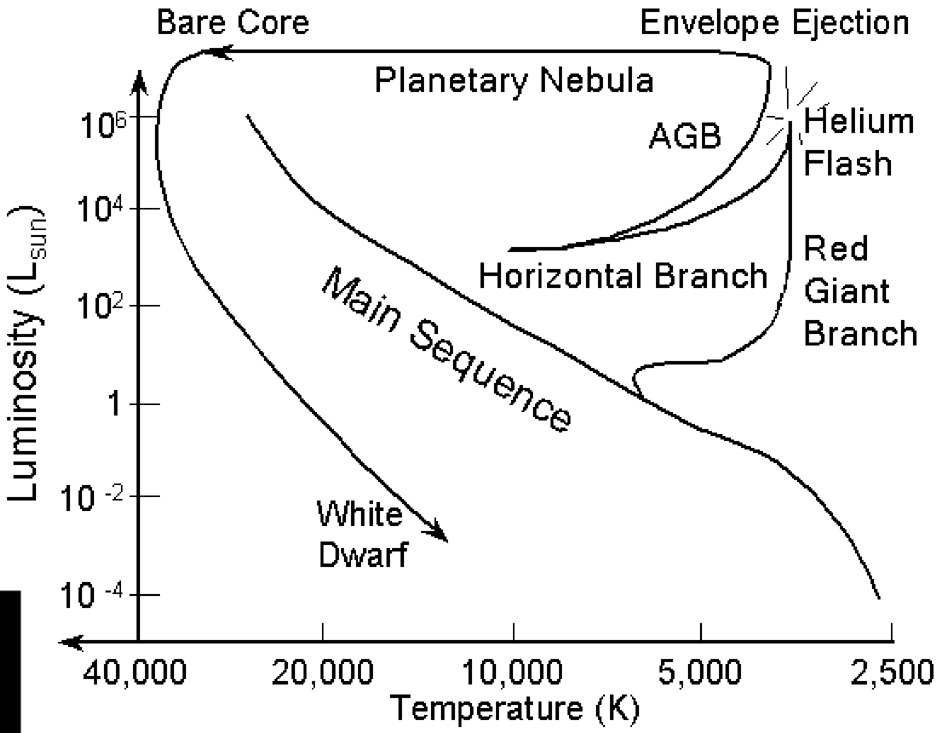
Red Giant Phase

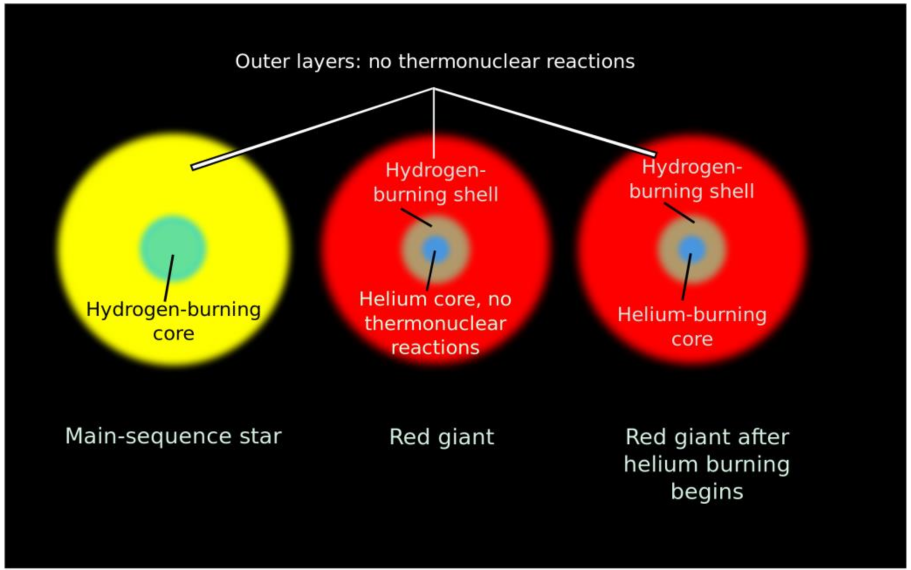
- With time, more helium “ash” adds into the core
- Core contracts more and becomes even hotter
- When the central temperature reaches 10^8 K, helium fusion ignites (***Helium Flash***) inside the core
- Helium fusion process (triple alpha process), converts helium to carbon



Helium Flash

Helium Flash takes only seconds





Helium Flash

- In low-mass star, the ***compressed core*** is in an ***electron-degeneracy state***
- ***Electron-degeneracy***: the ***electrons*** are so closely packed that they ***can not be further compressed***, due to the ***Pauli exclusion principle***
- ***Pauli exclusion principle***: two particles can not occupy the same quantum state
- The ***core*** becomes supported by ***degenerate-electron pressure,*** i.e ***independent of temperature***
- As ***helium fusion ignites*** in the core, ***temperature rises exponentially***, but ***pressure does not rise***

Helium Flash

- ***Helium fusion rate rises exponentially*** => Helium Flash
- During the time of Helium Flash, the ***core*** is ***extremely bright*** ($10^{12}\ L_{\odot}$)
- At certain core temperature ***no longer electron-degeneracy state*** => core becomes an ***ideal gas***
- The ***core expands***, and ***cools***, terminating the Helium Flash
- The ***core*** becomes a ***steady state*** of ***helium fusion***
- A red giant enters into the stage of "***Horizontal Branch***" in the HRD

Horizontal Branch

- Red Giant becomes ***less luminous*** and ***smaller***, but ***hotter***
- ***Steady State*** of helium fusion in core: ***no contraction*** and ***no temperature rising***
- The ***core*** acts like an ***ideal gas***:
  1. Temperature increases, core expands
  2. Core expands, temperature decreases
- Shell hydrogen fusion rate drops => lower luminosity
- Red Giant shrinks because of less energy output
- It becomes hotter at surface as it compresses