ASTR367

Stellar Evolution

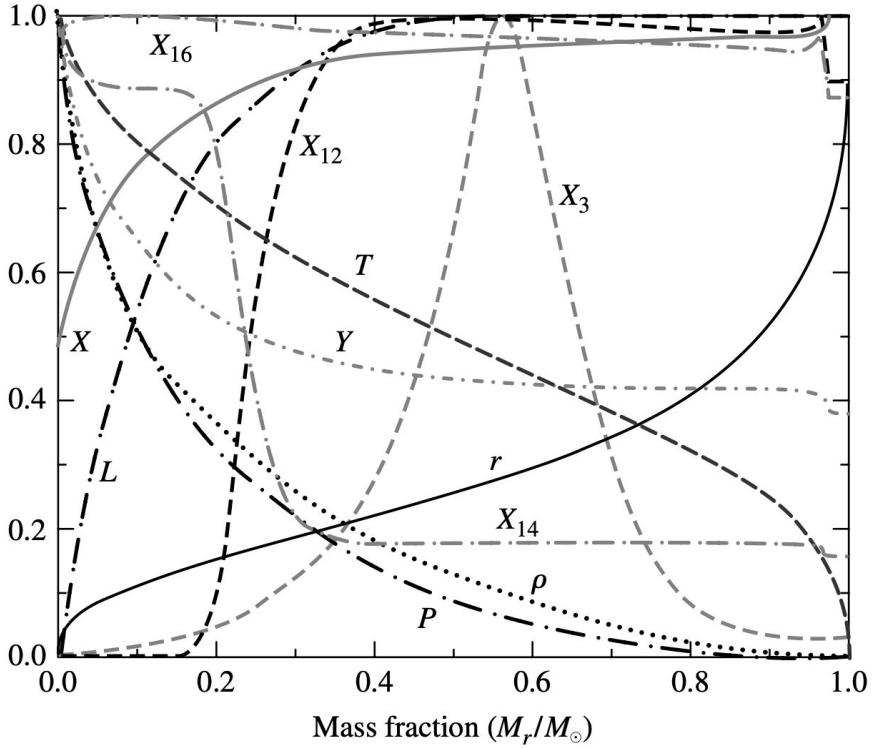


FIGURE 2 The interior structure of the present-day Sun (a 1 $M_\odot$ star), 4.57 Gyr after reaching the ZAMS. The model is located between points 1 and 2 in Fig. 1. The maximum ordinate values of the parameters are $r = 1.0\ R_\odot$, $L = 1.0\ L_\odot$, $T = 15.69 \times 10^6$ K, $\rho = 1.527 \times 10^5$ kg m^{-3}, $P = 2.342 \times 10^{16}$ N m^{-2}, $X = 0.73925$, $Y = 0.64046$, $X_3 = 3.19 \times 10^{-3}$, $X_{12} = 3.21 \times 10^{-3}$, $X_{14} = 5.45 \times 10^{-3}$, and $X_{16} = 9.08 \times 10^{-3}$. (Data from Bahcall, Pinsonneault, and Basu, *Ap. J.*, *555*, 990, 2001.)

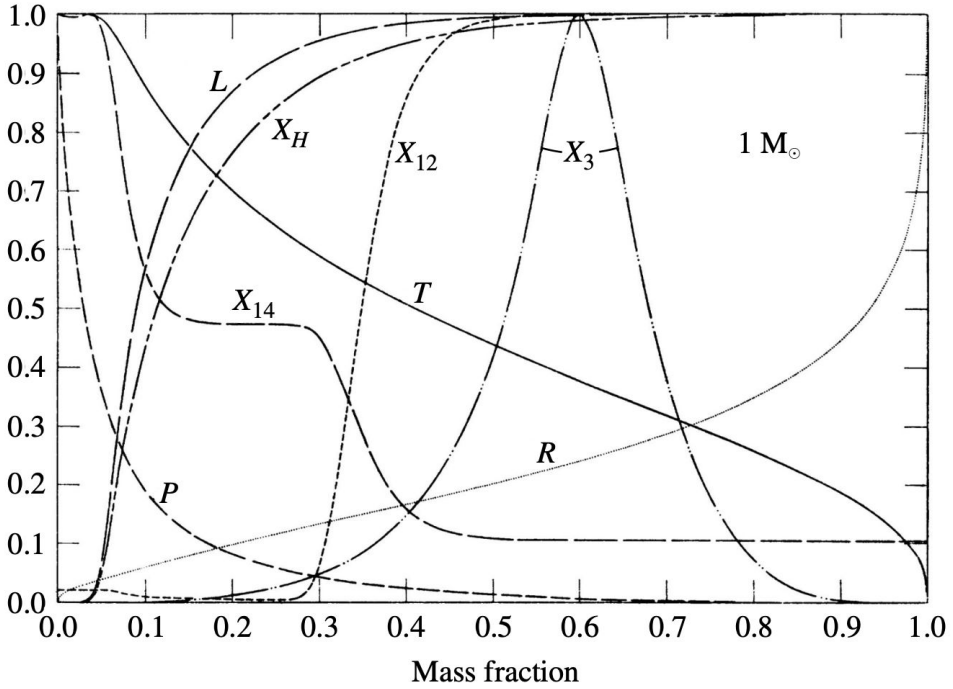
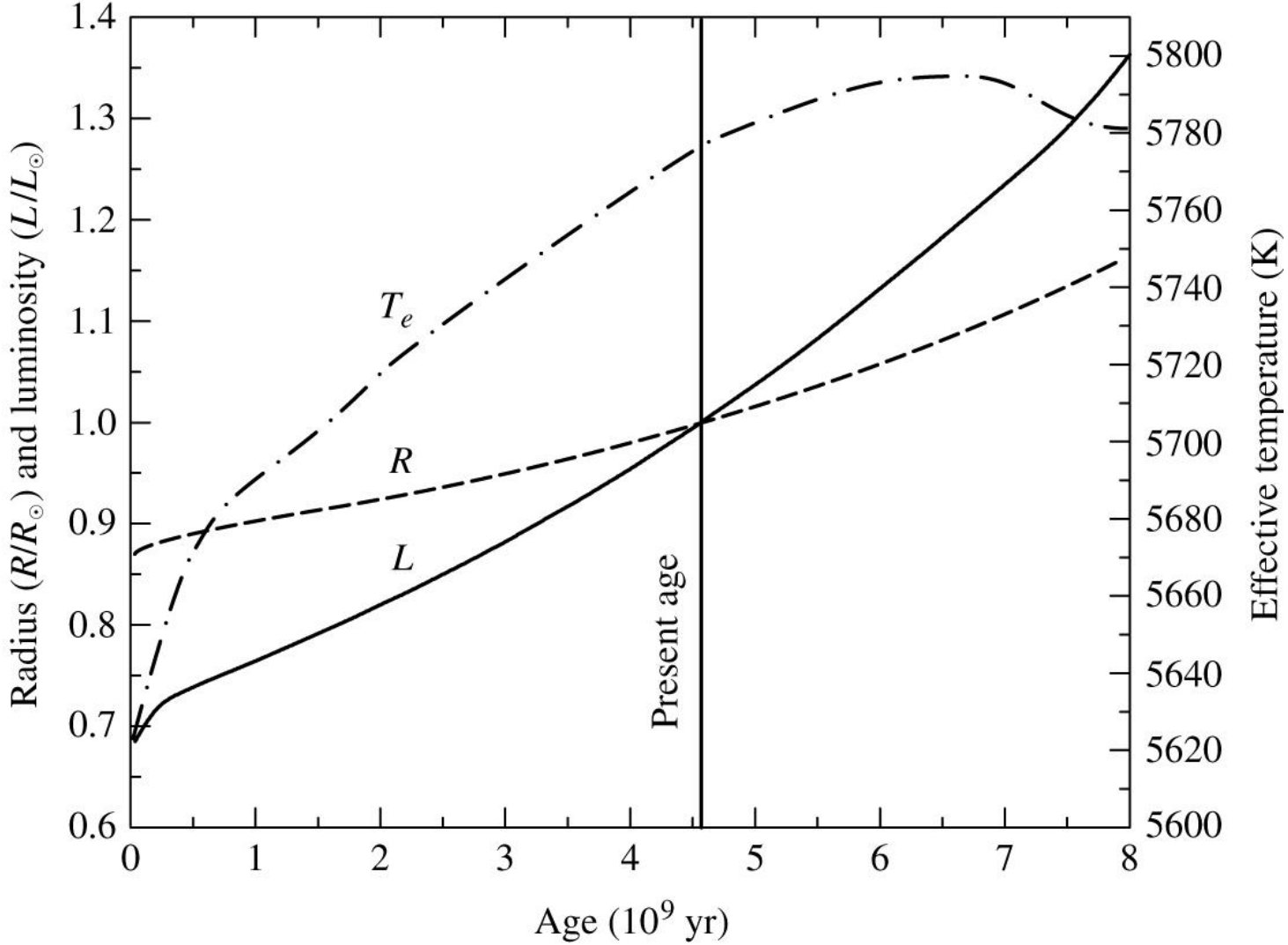
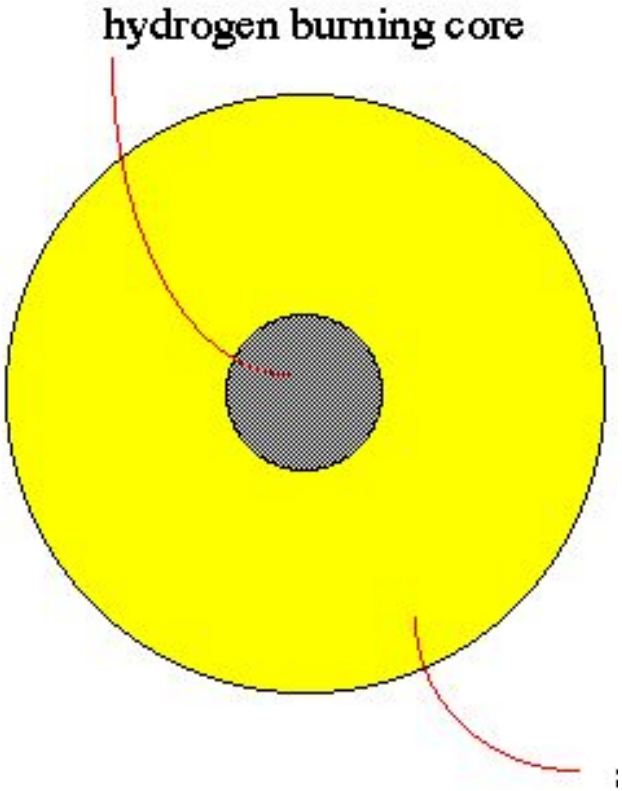


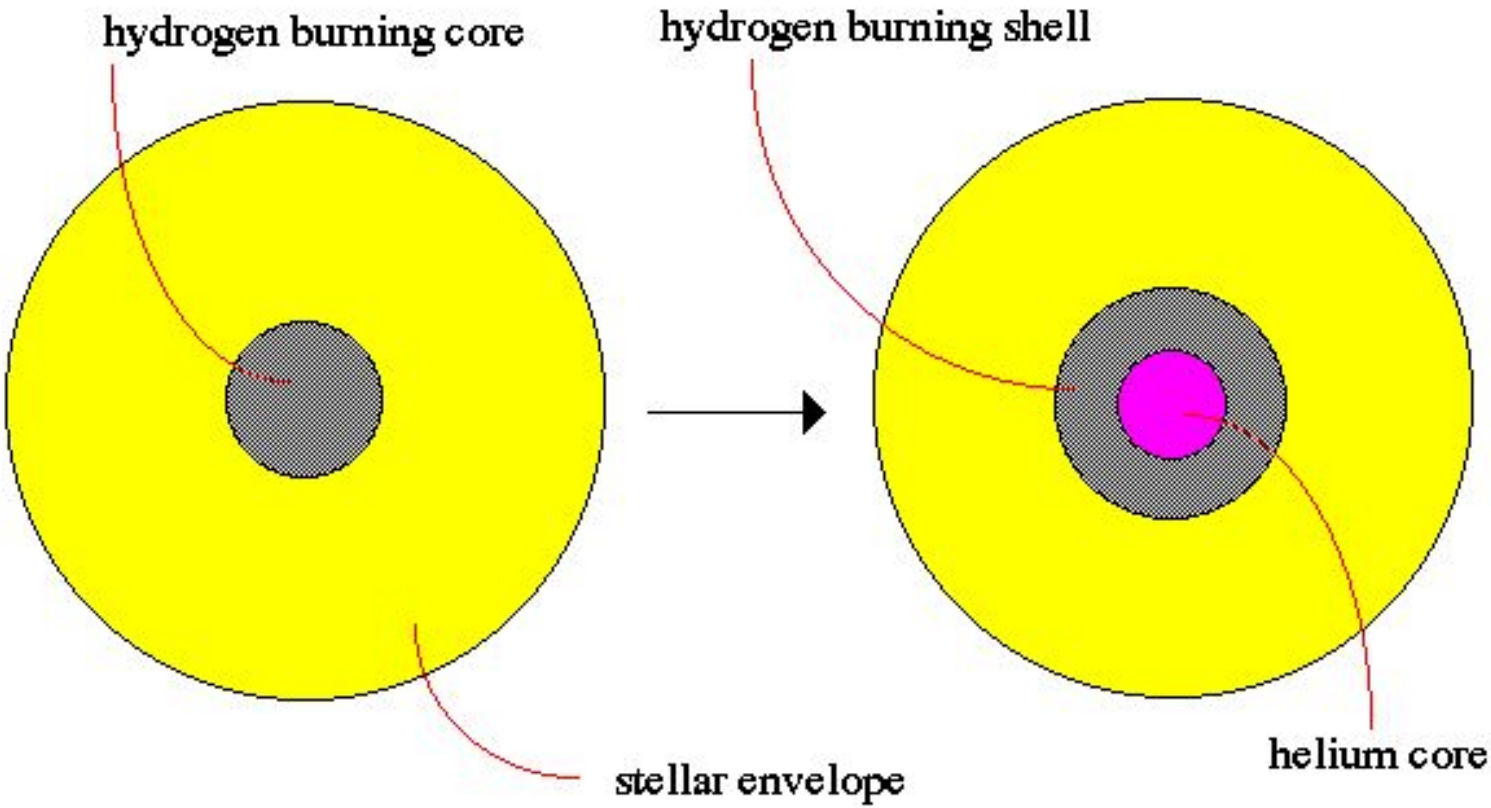
FIGURE 3 The interior structure of a 1 $M_\odot$ star near point 3 in Fig. 1, as described by the pioneering calculations of Icko Iben. Although specific values of quantities in modern models differ somewhat from those given here, state-of-the-art models do not significantly differ qualitatively from these calculations. The maximum ordinate values of the parameters for the Iben model are $R = 1.2681\ R_\odot$, $P = 1.3146 \times 10^{17}\ N\ m^{-2}$, $T = 19.097 \times 10^6\ K$, $L = 2.1283\ L_\odot$, $X_H = 0.708$, $X_3 = 5.15 \times 10^{-3}$, $X_{12} = 3.61 \times 10^{-3}$, and $X_{14} = 1.15 \times 10^{-2}$. The radius of the star is $1.3526\ R_\odot$. (Figure adapted from Iben, *Ap. J.*, *47*, 624, 1967.)

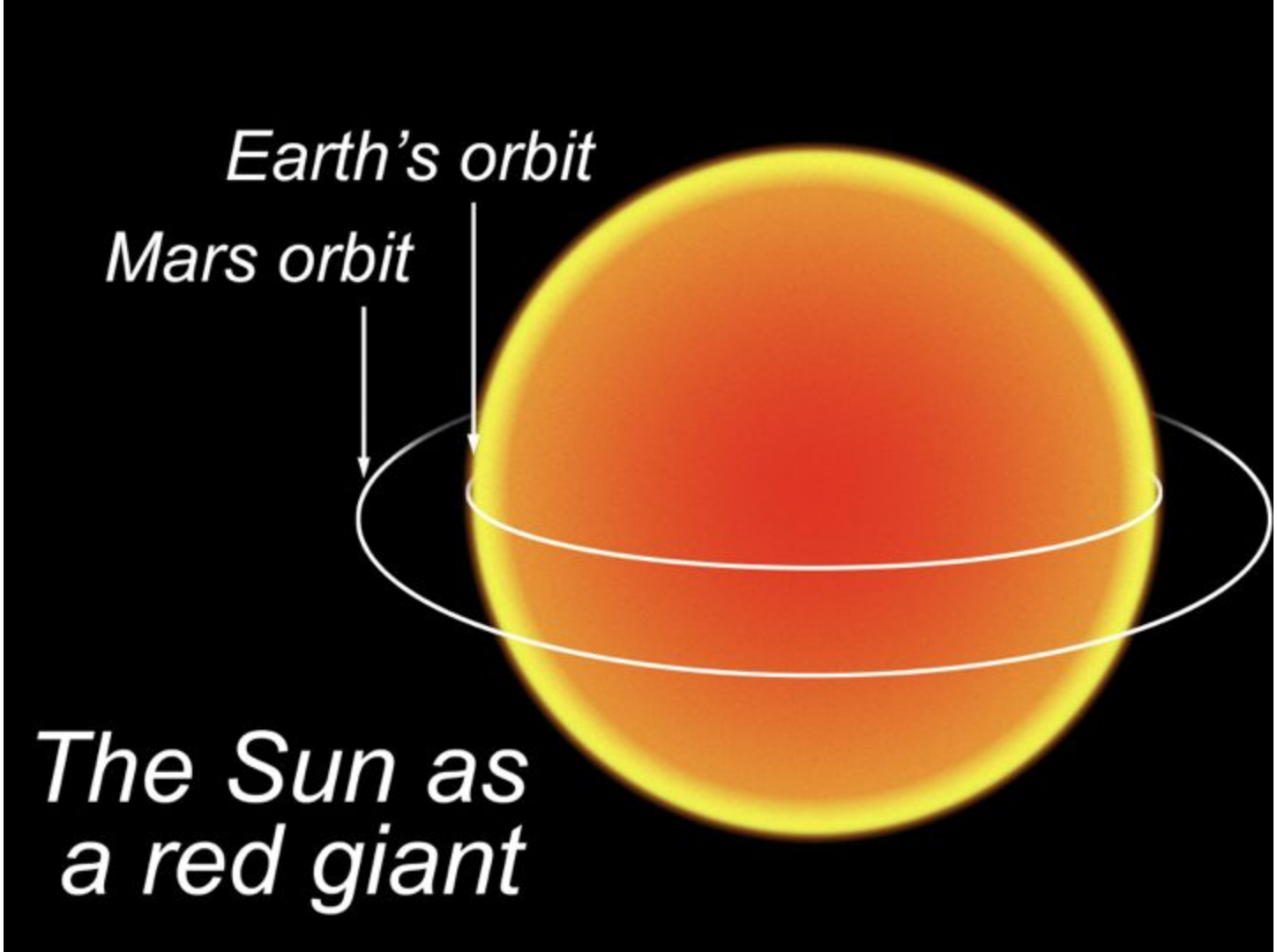

Radius ($R/R_\odot$) and luminosity ($L/L_\odot$)
Effective temperature (K)
Age (10^9 yr)
T_e
R
L
Present age
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
5800
5780
5760
5740
5720
5700
5680
5660
5640
5620
5600
0
1
2
3
4
5
6
7
8

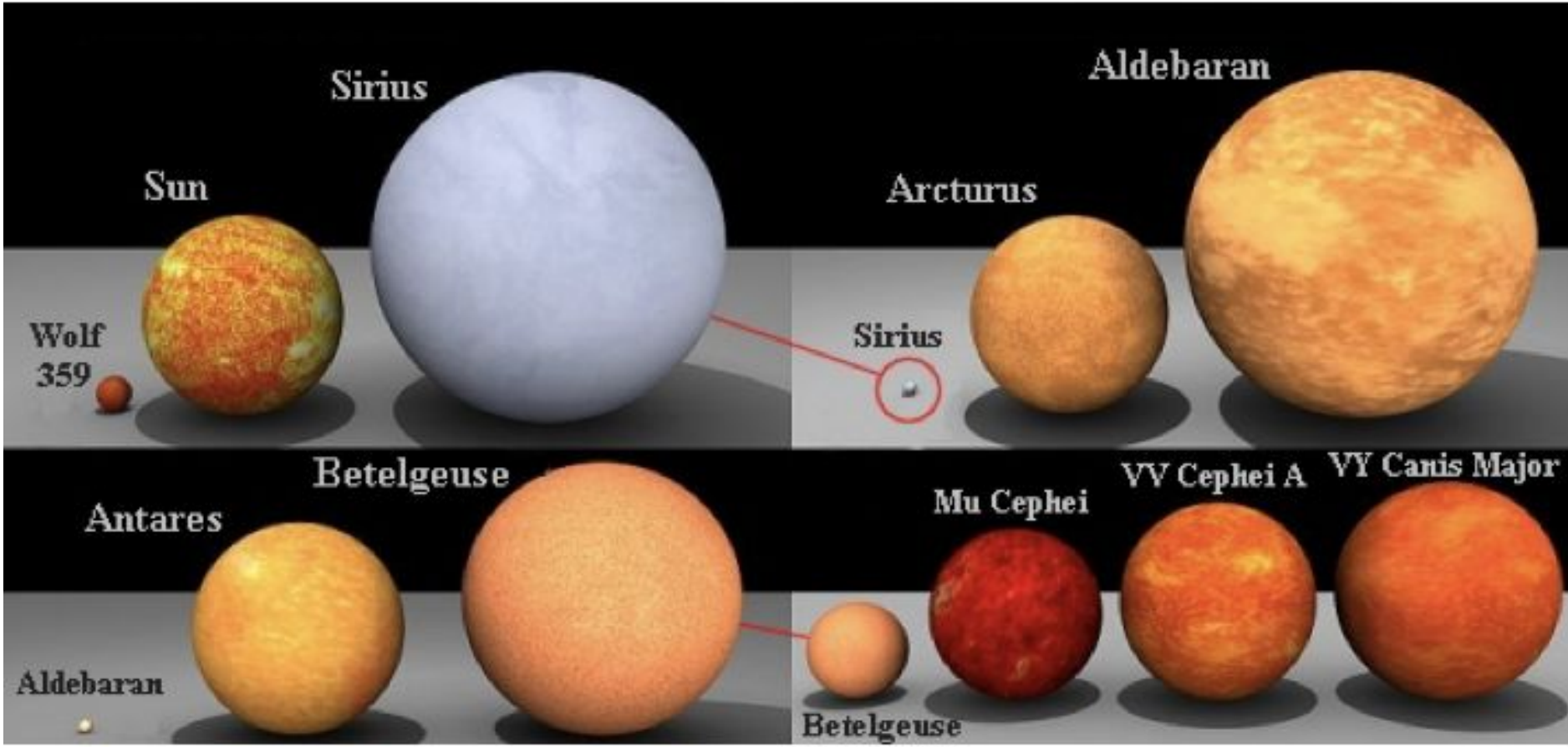
Core Exhaustion



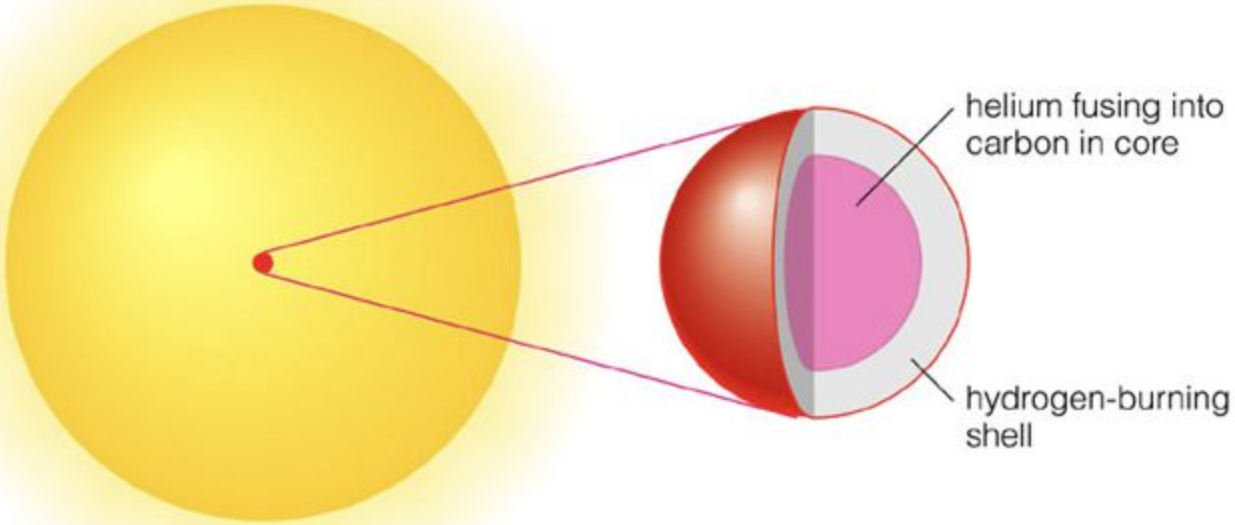
Core Exhaustion




Earth's orbit
Mars orbit
The Sun as
a red giant

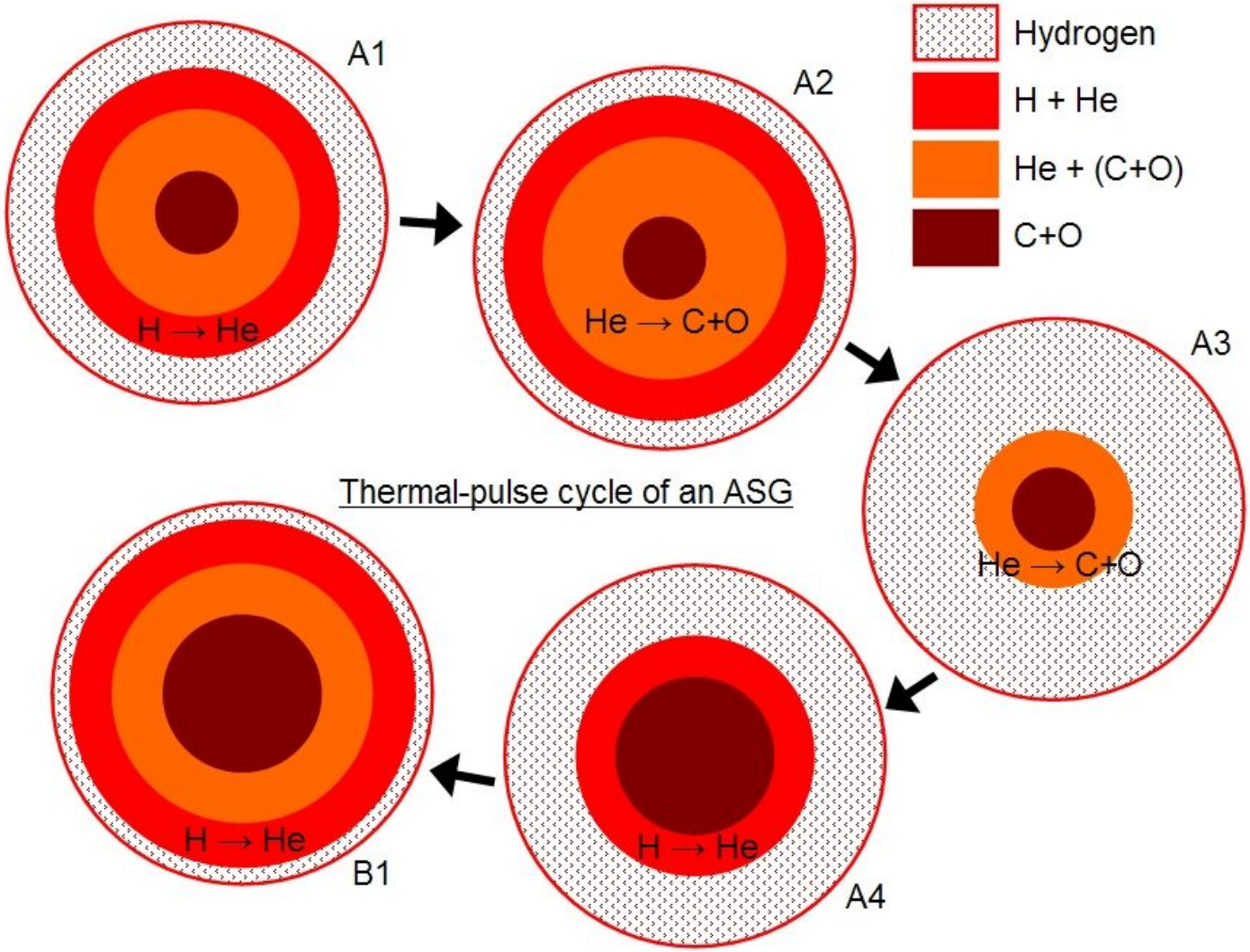

Sirius
Sun
Wolf
359
Aldebaran
Arcturus
Sirius
Betelgeuse
Antares
Aldebaran
Mu Cephei
VV Cephei A
VY Canis Major
Betelgeuse

Helium Burning

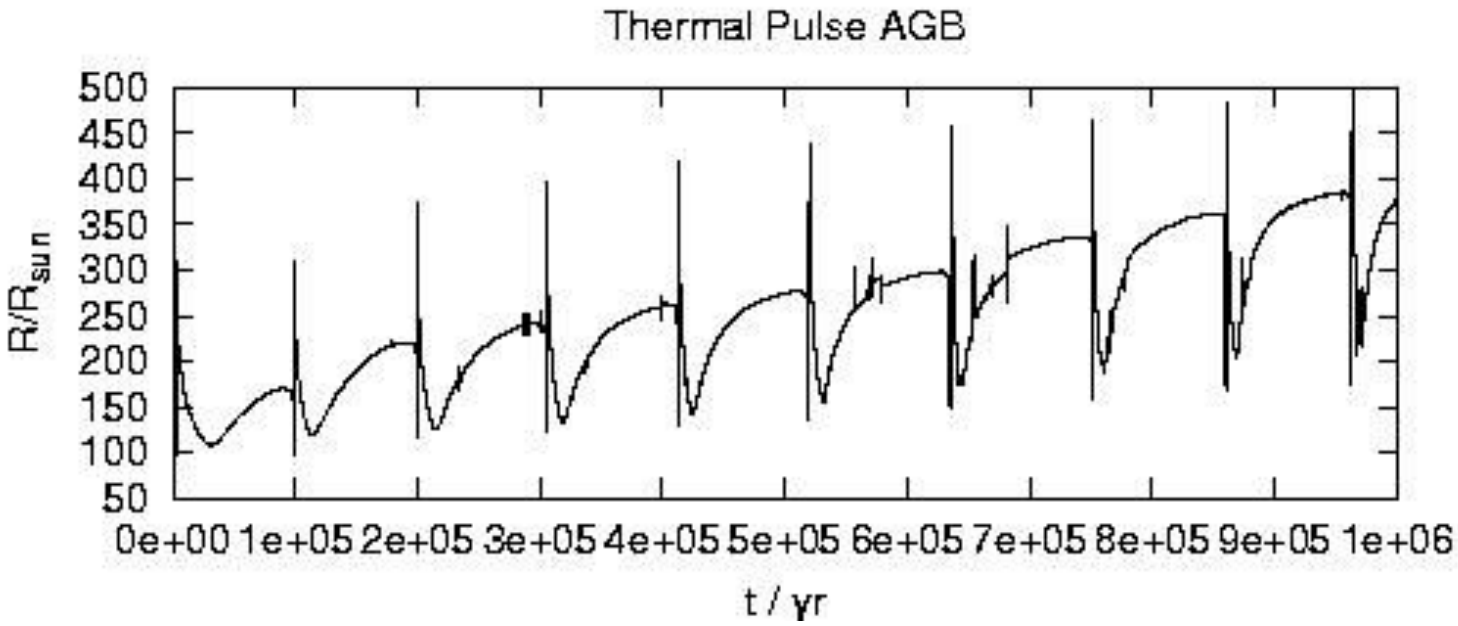


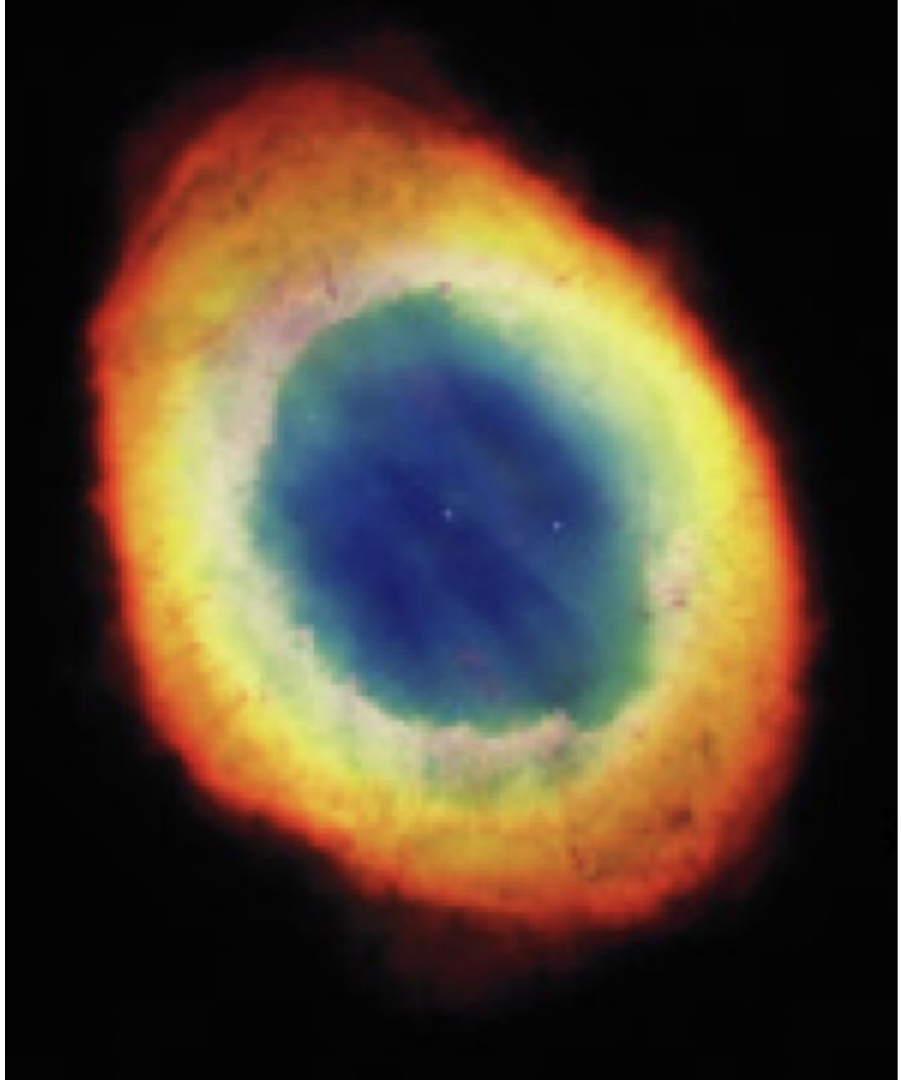
Helium burning stars neither shrink nor grow because core thermostat is temporarily fixed.

Gravity balances pressure … for now

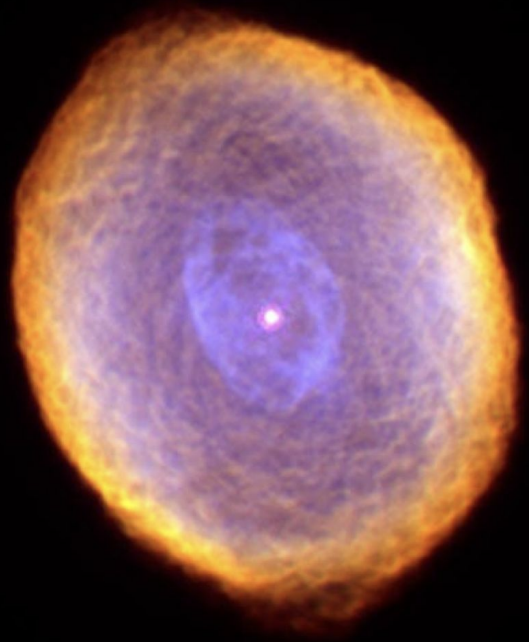


Thermal-pulse cycle of an ASG


Thermal Pulse AGB
R/R_sun
500
450
400
350
300
250
200
150
100
50
0e+00
1e+05
2e+05
3e+05
4e+05
5e+05
6e+05
7e+05
8e+05
9e+05
1e+06
t / yr

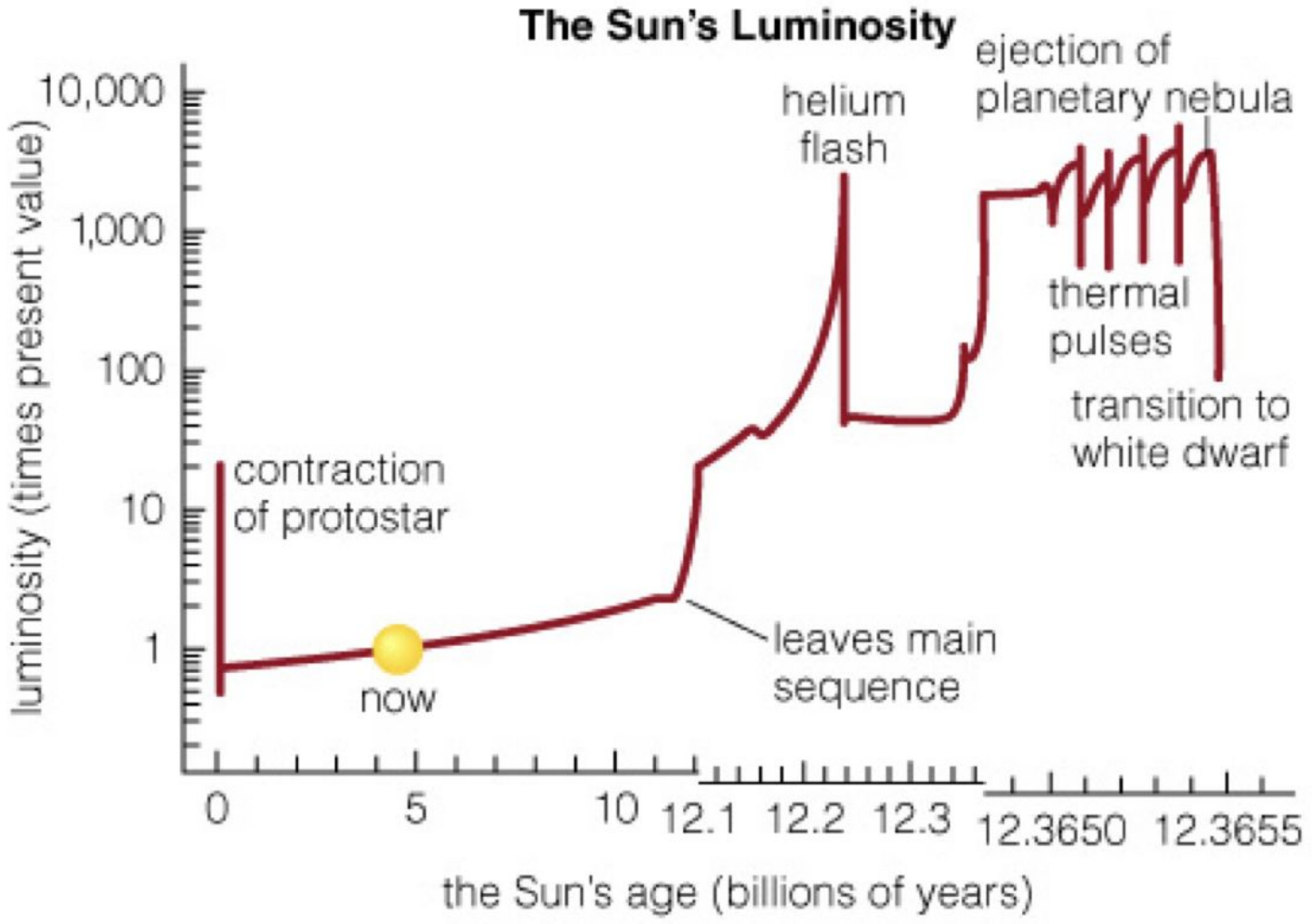


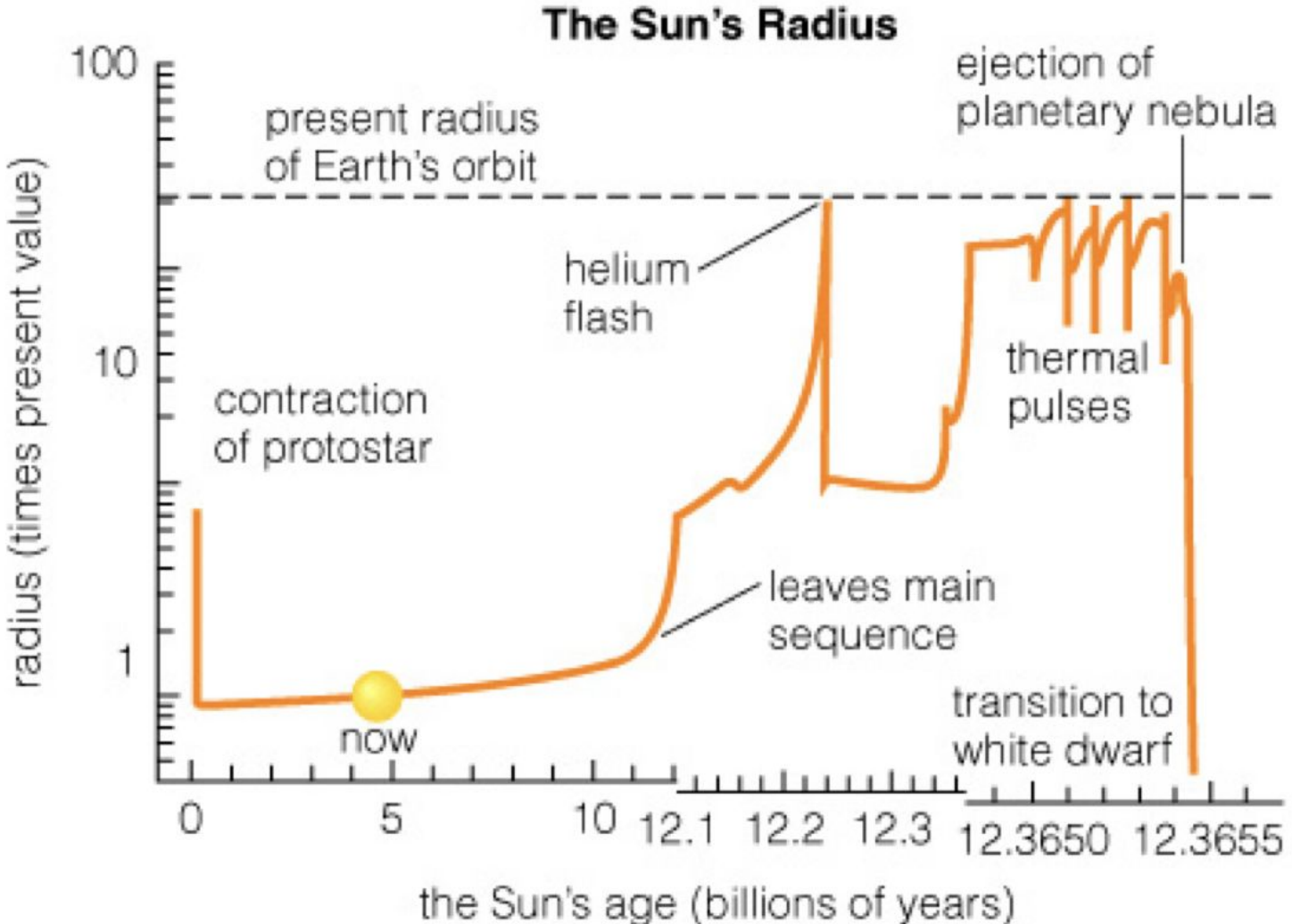
Planetary Nebula IC 418

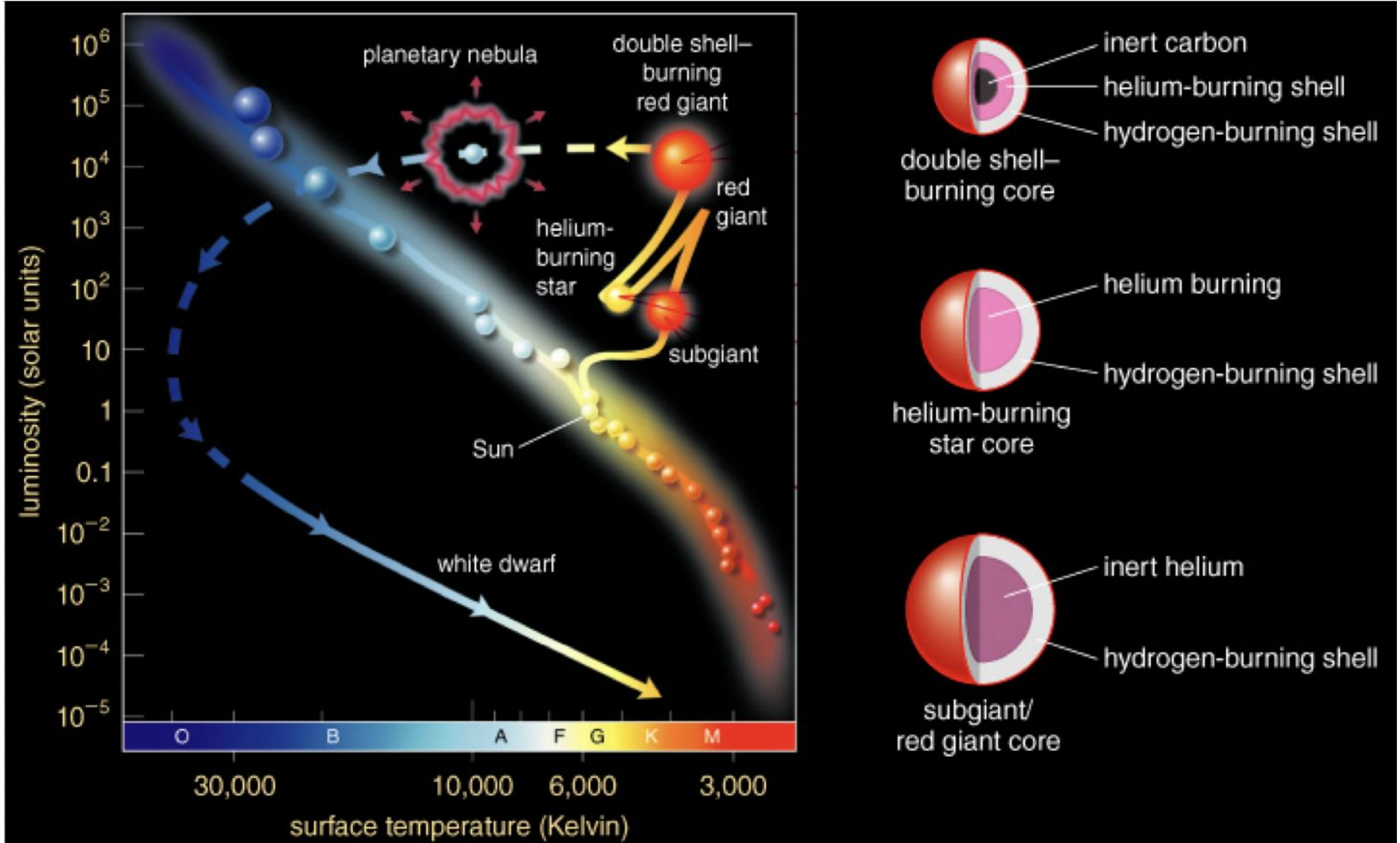


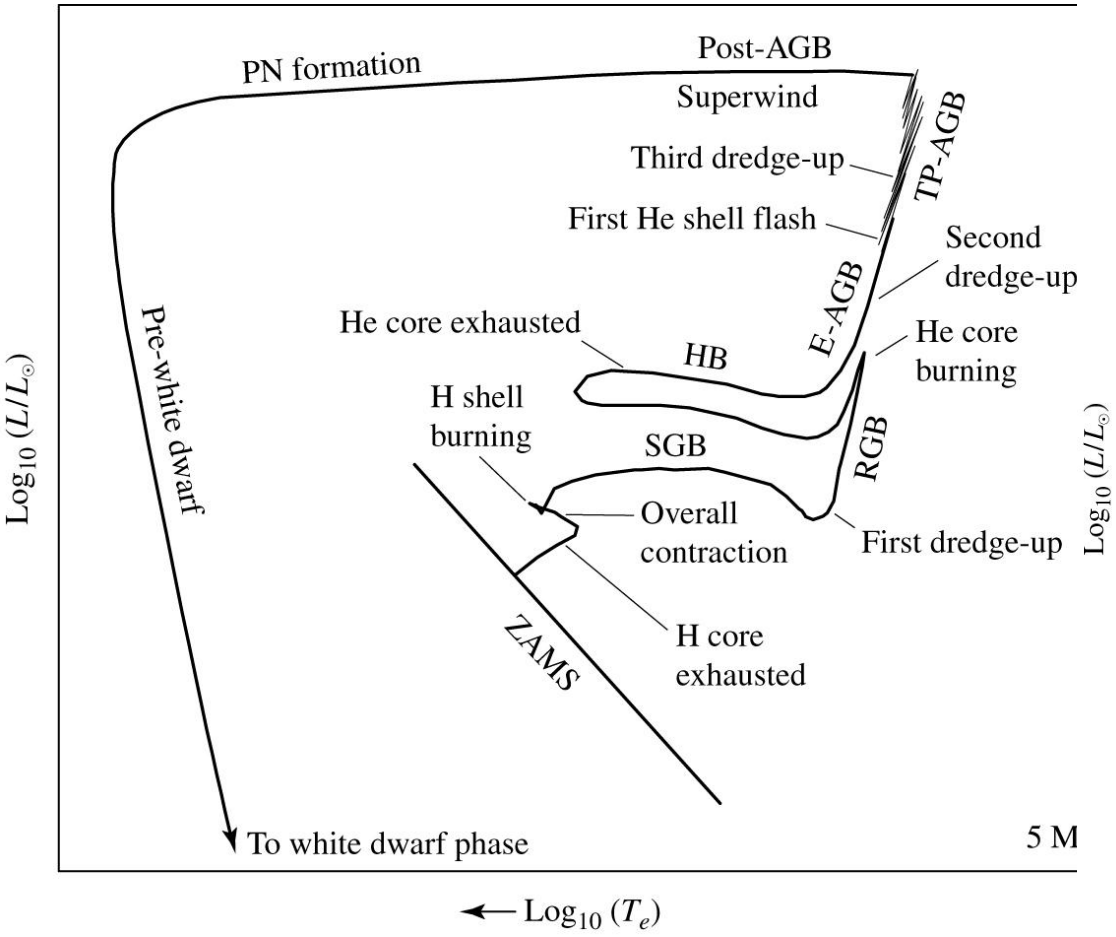
Hubble Heritage

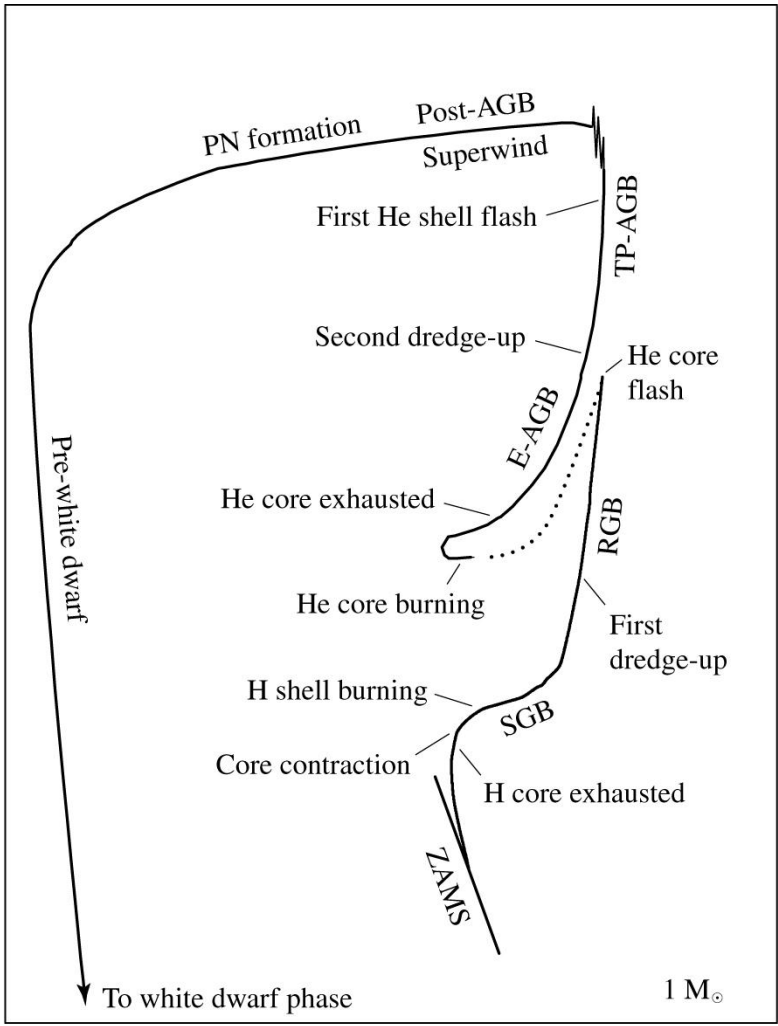
PRC00-28 • NASA and The Hubble Heritage Team (STScI/AURA) • HST/WFPC2


The Sun's Luminosity
luminosity (times present value)
10,000
1,000
100
10
1
helium flash
ejection of planetary nebula
thermal pulses
transition to white dwarf
contraction of protostar
now
leaves main sequence
0
5
10
12.1
12.2
12.3
12.3650
12.3655
the Sun's age (billions of years)


The Sun's Radius
100
10
1
radius (times present value)
present radius
of Earth's orbit
ejection of
planetary nebula
helium
flash
thermal
pulses
contraction
of protostar
leaves main
sequence
now
transition to
white dwarf
0
5
10
12.1
12.2
12.3
12.3650
12.3655
the Sun's age (billions of years)

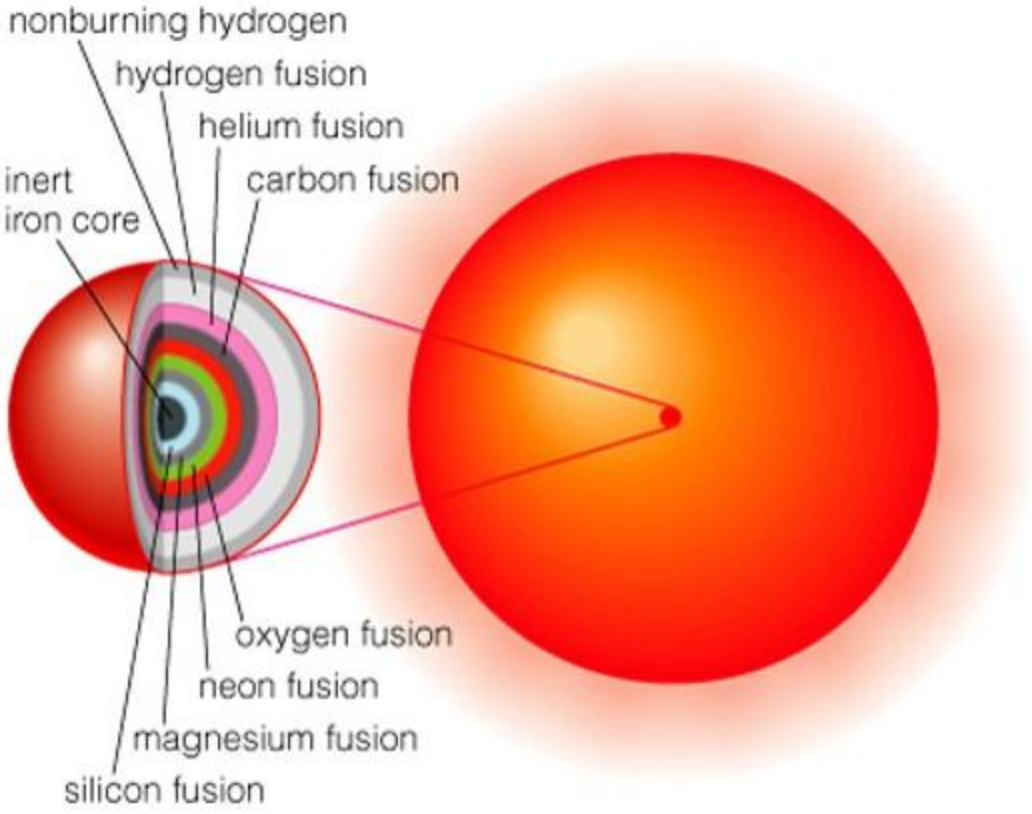

planetary nebula
double shell–burning red giant
red giant
helium-burning star
subgiant
Sun
white dwarf
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)
inert carbon
helium-burning shell
hydrogen-burning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

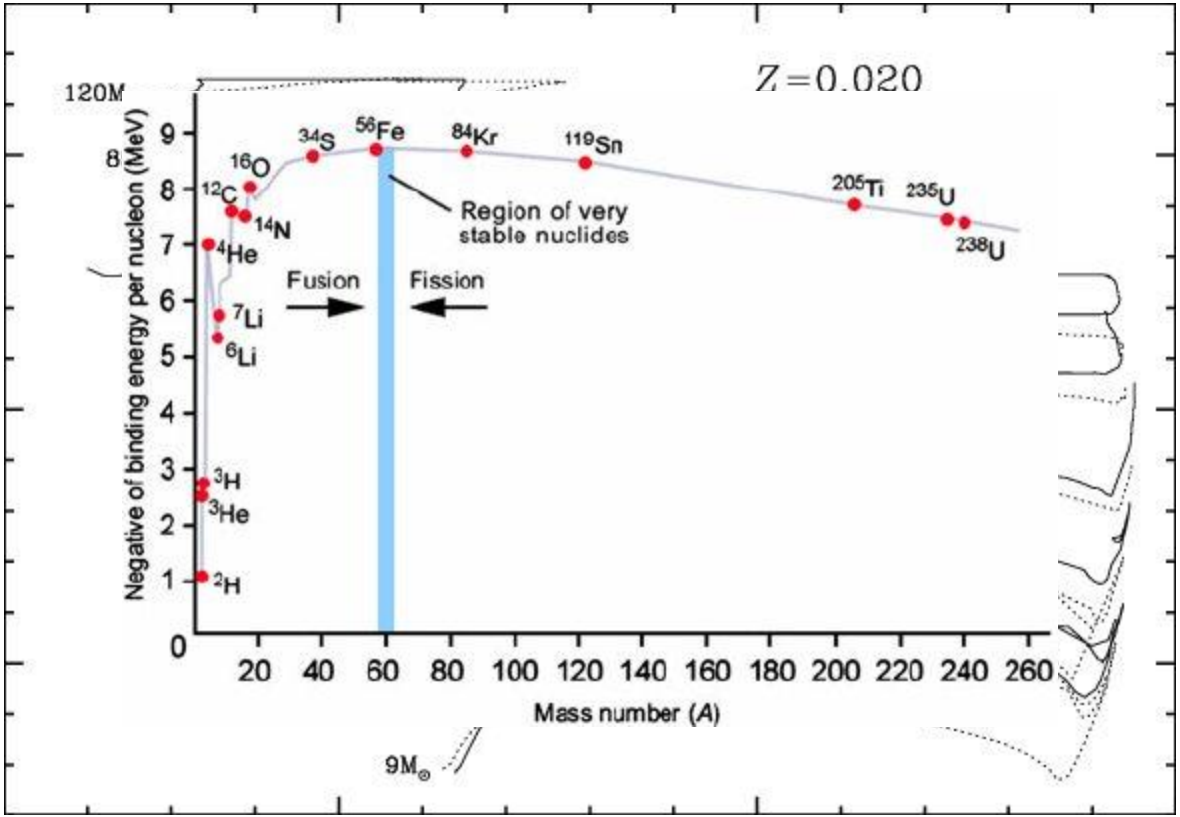


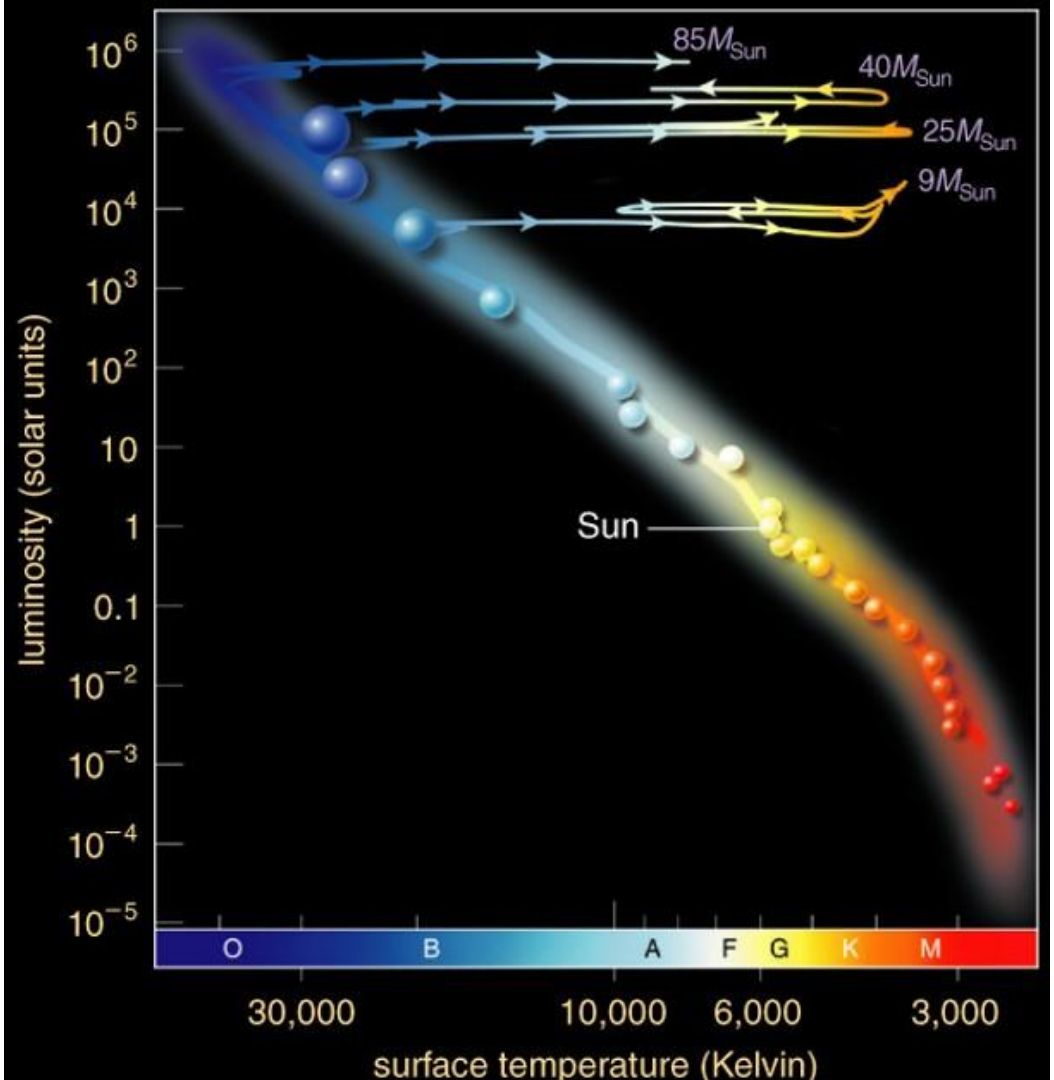


5-8 Msun ↑

<5 Msun →


nonburning hydrogen
hydrogen fusion
helium fusion
carbon fusion
inert
iron core
oxygen fusion
neon fusion
magnesium fusion
silicon fusion


Z = 0.020
120M
9M⊙
Negative of binding energy per nucleon (MeV)
Mass number (A)
Region of very stable nuclides
Fusion
Fission
^{56}Fe
^{34}S
^{84}Kr
^{119}Sn
^{16}O
^{12}C
^{14}N
^{4}He
^{7}Li
^{6}Li
^{3}H
^{3}He
^{2}H
^{205}Ti
^{235}U
^{238}U


$85M_{Sun}$
$40M_{Sun}$
$25M_{Sun}$
$9M_{Sun}$
Sun
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}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
surface temperature (Kelvin)

Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.732	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.971	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.414	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [278]	110 Ds Darmstadtium [281]	111 Rg Roentgenium [280]	112 Cn Copernicium [285]	113 Nh Nihonium [286]	114 Fl Flerovium [289]	115 Mc Moscovium [289]	116 Lv Livermorium [293]	117 Ts Tennessine [294]	118 Og Oganesson [294]

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.243	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali Metal | Alkaline Earth | Transition Metal | Basic Metal | Semimetal | Nonmetal | Halogen | Noble Gas | Lanthanide | Actinide

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$$M > 85\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{LBV} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

$$40\,\mathrm{M}_\odot < M < 85\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{Of} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

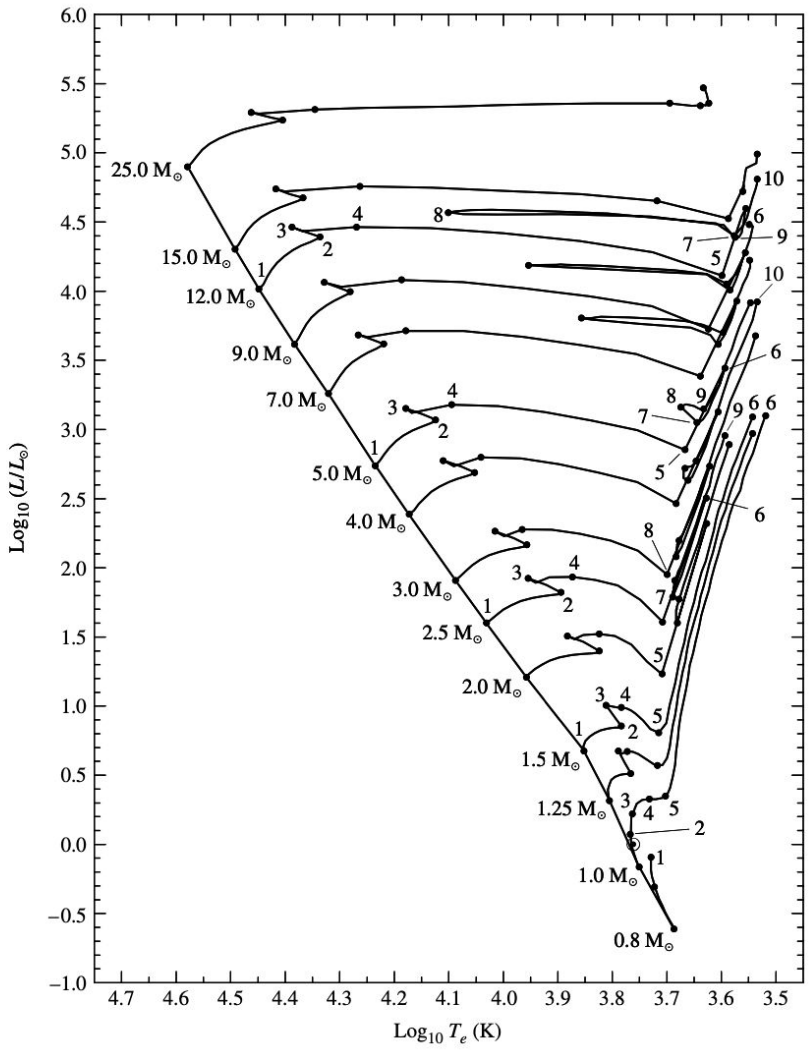
$$25\,\mathrm{M}_\odot < M < 40\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{WC} \rightarrow \mathrm{SN}$$

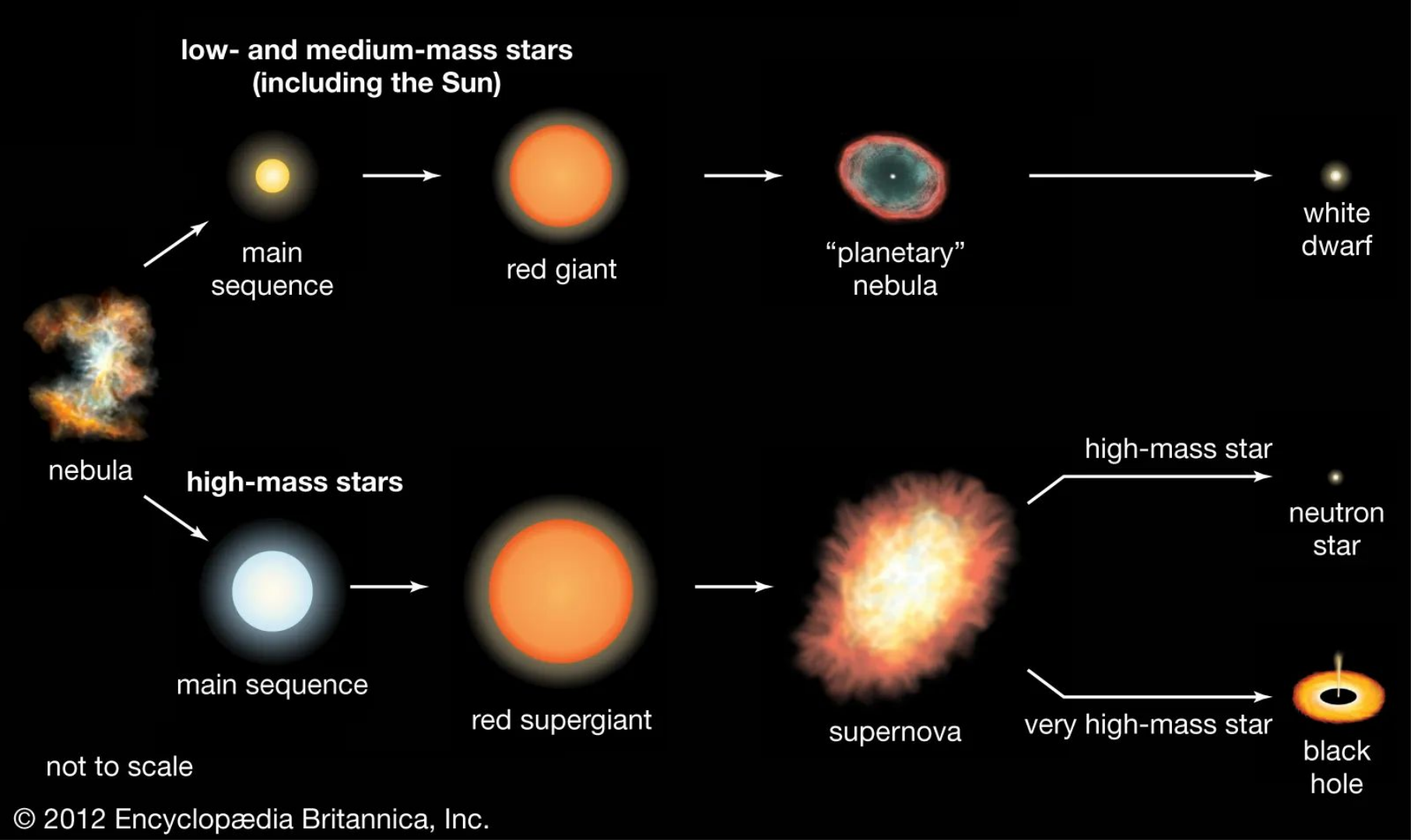
$$20\,\mathrm{M}_\odot < M < 25\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{WN} \rightarrow \mathrm{SN}$$

$$10\,\mathrm{M}_\odot < M < 20\,\mathrm{M}_\odot : \mathrm{O} \rightarrow \mathrm{RSG} \rightarrow \mathrm{BSG} \rightarrow \mathrm{SN}$$

TABLE 1 The elapsed times since reaching the zero-age main sequence to the indicated points in Fig. 1, measured in millions of years (Myr). (Data from Schaller et al., *Astron. Astrophys. Suppl.*, *96*, 269, 1992.)

Initial Mass ($M_\odot$)	1	2	3	4	5
	6	7	8	9	10
25	0	6.33044	6.40774	6.41337	6.43767
	6.51783	7.04971	7.0591		
15	0	11.4099	11.5842	11.5986	11.6118
	11.6135	11.6991	12.7554		
12	0	15.7149	16.0176	16.0337	16.0555
	16.1150	16.4230	16.7120	17.5847	17.6749
9	0	25.9376	26.3886	26.4198	26.4580
	26.5019	27.6446	28.1330	28.9618	29.2294
7	0	42.4607	43.1880	43.2291	43.3388
	43.4304	45.3175	46.1810	47.9727	48.3916
5	0	92.9357	94.4591	94.5735	94.9218
	95.2108	99.3835	100.888	107.208	108.454
4	0	162.043	164.734	164.916	165.701
	166.362	172.38	185.435	192.198	194.284
3	0	346.240	352.503	352.792	355.018
	357.310	366.880	420.502	440.536	
2.5	0	574.337	584.916	586.165	589.786
	595.476	607.356	710.235	757.056	
2	0	1094.08	1115.94	1117.74	1129.12
	1148.10	1160.96	1379.94	1411.25	
1.5	0	2632.52	2690.39	2699.52	2756.73
	2910.76				
1.25	0	4703.20	4910.11	4933.83	5114.83
	5588.92				
1	0	7048.40	9844.57	11386.0	11635.8
	12269.8				
0.8	0	18828.9	25027.9		





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