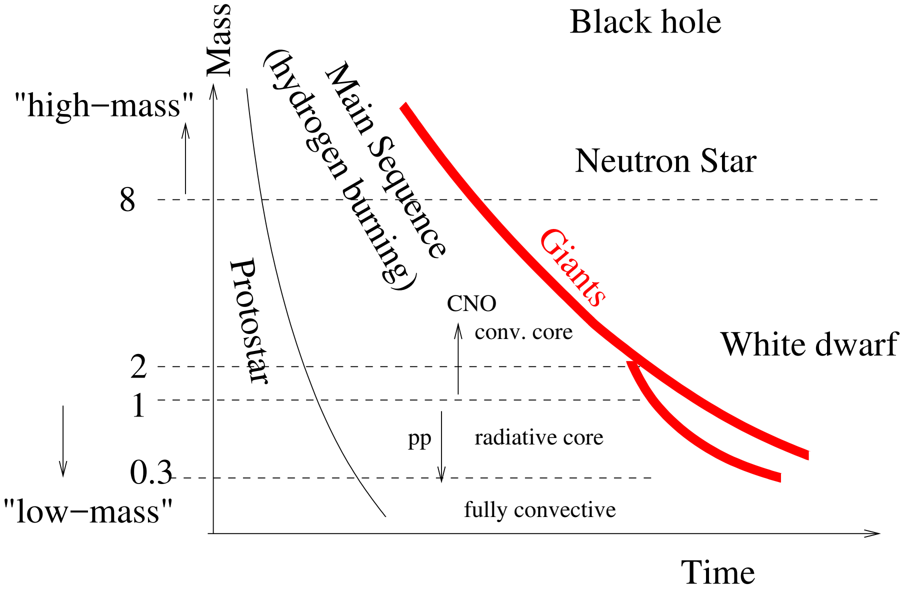
24 Stars notes 2019/10/25 - Fri - evolution during core H burning

Mention test suite and mesastar.org as sources for MESA projects. Will need to send me an email with 1-paragraph summary on due date (Nov 4).

24.1 Evolution on the Main Sequence

How the star changes during the hydrogen burning phase.



Want to understand how the star changes its structure while still burning hydrogen. The main reason that this can be done is that there is a hierachy of timescales. The time on the main sequence is

$$t_{MS} = \frac{E_{nuc}}{L} = \frac{E_{nuc}/m_p}{E_{th}/m_p} t_{KH}$$

since the evolution time on the main sequence is much longer than the Kelvin-Helmlotz time, the star evolves from one solution to another where each solution is in balance:

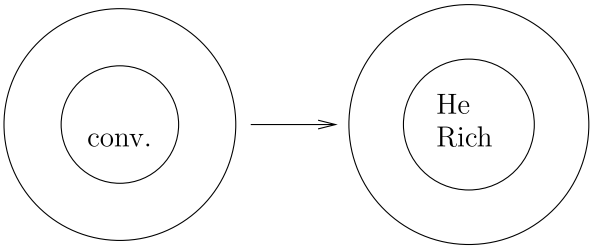
$$T\frac{ds}{dt} = 0 = \epsilon_{nuc} - \frac{\partial L_r}{\partial m_r}$$

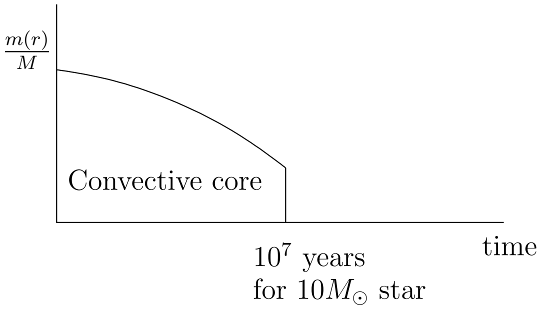
This made modeling much easier in the past.

Evolution during this time is one of changing the composition (H→He) from one thermal equilibrium state to another.

24.2 Massive stars

$M > M_\odot$: Convective core, burning via CNO cycle (H to He), has a radiative envelope. What is the main thing that's changing with time?





Big point is that converting H to He reduces the number of particles exerting pressure (per unit mass). 8 particles become 3.

Writing down:

$$P = \frac{\rho k T}{\mu m_p} = \frac{\rho k T}{m_p}[2X + \tfrac{3}{4}Y]$$

where Y is the He mass fraction and X is the Hydrogen mass fraction. for Hydrogen + 0.25 helium, $\mu = 0.6$ and for pure He $\mu = 4/3$. The virial theorem is still satisfied so

$$kT \simeq \frac{GM\mu m_p}{R}$$

the nuclear burning is very temperature sensative, so a rise in temperature dumps energy into the star, causing it to expand and cool.

So because the CNO cycle is so temperature sensative, T_c stays approximately constant and the star readjusts to increasing μ by increasing R.

How does changing μ effect the heat transport?

$$L \sim 4\pi R^2 \frac{c}{3\kappa\rho}\frac{1}{R} a T^4$$

and

$$\kappa = 0.2(1 + X) cm^2/gram$$

for electron scattering. Using $\rho \propto M/R^3$ and assuming T is constant, and thus $R \propto \mu$,

$$L \propto \frac{R}{\kappa\rho} \propto \frac{R^4}{\kappa} \propto \frac{\mu^4}{1+X}$$

so the luminosity increases with μ. So we see that the star's luminosity increases and also does it's radius, to keep the core temperature fixed.

Note that for that scaling

$$\frac{L_{pure\ He}}{L_{cosmic}} = 40$$

this is really too much because only the inner regions actually become pure helium. The change in radius goes like $R \propto \mu$ implies a factor of 2 in radius. This really does occur.

Reference to figure below with HR evolution diagram. You can see increase in luminosity, A to B. Massive stars evolve on the main sequence by increasing radius and L. Also see MESA paper 1, figures 14 and 22.

Table 26.7

Evolutionary Phases in Fig. 26.10 and Fig. 26.11

Phase	*Segment of Track or Point(s)*	*Discussed in Sect.*
MS	A-B	26.4a
Central H exhaustion	B-C	26.4b
H burning shell source	C-E	26.4c
Deep convective envelope	D, K	26.4c
Core He burning	E-F	26.4d
Central He exhaustion	F-G	26.4e
He burning shell source	G-H-K	26.4f
Cessation of H burning shell source	H	26.4g

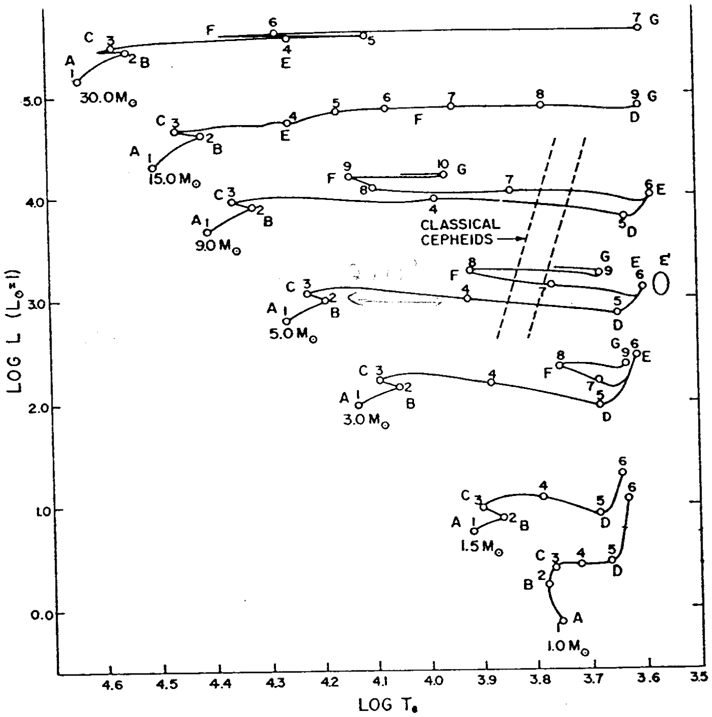


Fig. 26.10 Post-MS evolutionary tracks on the theoretical H-R diagram for stars having masses in the range $1.0 \leq M \leq 30.0$ and, initially, a "Population I" composition ($X = 0.708$, $Z = 0.02$ for all tracks except the $M = 30$ track; for this track, $X = 0.70$, $Z = 0.03$). Numbered points along the tracks are those listed in Table 26.2. The significance of the letters alongside the tracks is summarized in Table 26.7 (*cf.* also Fig. 26.12 below). The tracks for $1.0 \leq M \leq 15.0$ are due to Iben [Ib64]; the track for $M = 30.0$ is due to Stothers [St66d]. The oval labelled E' is the region where the "helium flash" occurs in stars with $M \approx 1.0-1.3$ (see Sect. 26.4c). The approximate location of the classical cepheids is also shown (see Chap. 27).

Evolutionary Lifetimes (Years)†

(*Initial composition:* $X = 0.708$, $Z = 0.02$ *for* $1.0 \leq M \leq 15.0$; $X = 0.70$, $Z = 0.03$ *for* $M = 30.0$)

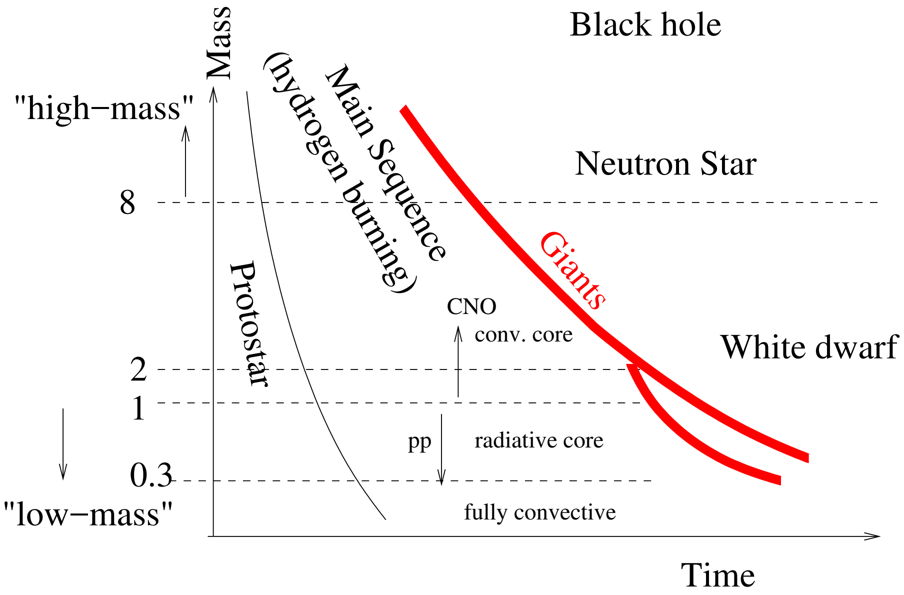
	M (solar units)						
Point	1.0	1.5	3.0	5.0	9.0	15.0	30.0
1	5.016(7)	1.821(7)	2.510(6)	5.760(5)	1.511(5)	6.160(4)	2 (4)
2	8.060(9)	1.567(9)	2.273(8)	6.549(7)	2.129(7)	1.023(7)	4.82(6)
3	9.705(9)	1.652(9)	2.394(8)	6.823(7)	2.190(7)	1.048(7)	4.91(6)
4	1.0236(10)	2.036(9)	2.478(8)	7.019(7)	2.208(7)	1.050(7)	4.92(6)
5	1.0446(10)	2.105(9)	2.488(8)	7.035(7)	2.213(7)	1.149(7)	4.93(6)
6	1.0875(10)	2.263(9)	2.531(8)	7.084(7)	2.214(7)	1.196(7)	5.45(6)
7	–	–	2.887(8)	7.844(7)	2.273(7)	1.210(7)	5.46(6)
8	–	–	3.095(8)	8.524(7)	2.315(7)	1.213(7)	–
9	–	–	3.262(8)	8.782(7)	2.574(7)	1.214(7)	–
10	–	–	–	–	2.623(7)	–	–

* Numbers in parentheses are the powers of ten by which the corresponding entries are to be multiplied.

† From Iben [Ib64] and Stothers [St66d].

24.3 Evolution on the Main Sequence for low mass stars

How the star changes during the hydrogen burning phase.



Massive stars evolve on the main sequence by increasing radius and L. see MESA paper 1, figure 22.

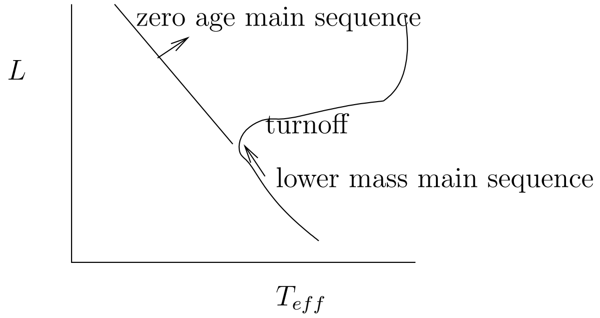
24.4 Low mass stars

$M < M_\odot$ radiative core, pp burning. in this case

$$L_{nuc} = \int \epsilon dm_r \propto T_c^{4\text{-}6}$$

so it is still true that L due to heat losses increses as μ increases. Because $L_{nuc} \propto T^4$ or so, the temperature must rise to match the increased energy loss rate. Not going to work this out. Looking at the $1.0 M_\odot$ evolution on the HR diagram we have, it moves parallel to the main sequence.

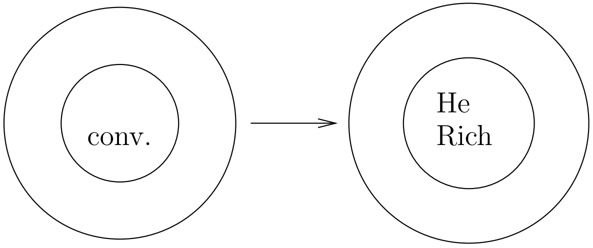
This makes dating of Globular clusters difficult. These have roughly ages of 10^{10} years so that the stars leaving the main sequence today have masses of ~ 0.9.

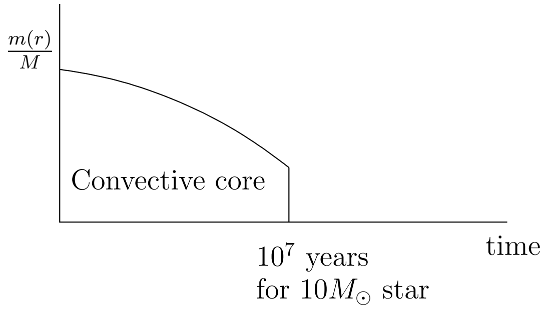


Also see MESA paper 1, figure 14. Current state of the art for ages of Globular clusters from MS. Turnoff provides the age to only ±2 Gyr.

24.5 H-depleted core formation

$M > M_\odot$: Convective core, burning via CNO cycle (H to He), has a radiative envelope.
$M < M_\odot$: radiative core, pp burning





Kippenhahn diagram. Can see that only the inner regions get burned. also the burning shuts off when the core is converted to helium, which is at 5.6 on the time axis.

Kippenhahn + Weigert

5 Mo

1.3 Mo

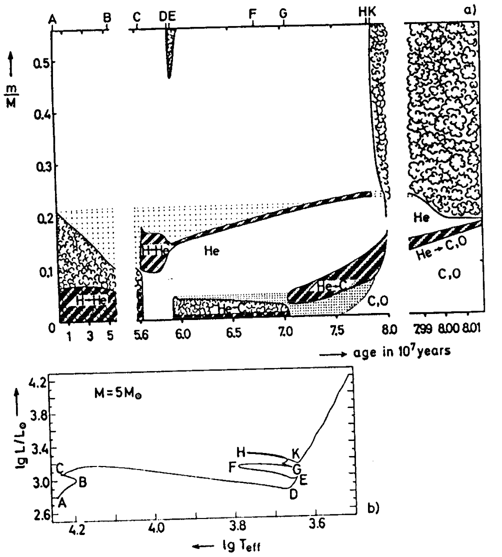


Fig. 31.2. (a) The evolution of the internal structure of a star of $5M_\odot$ of extreme population I. The abscissa gives the age after the ignition of hydrogen in units of 10^7 years; each vertical line corresponds to a model at a given time. The different layers are characterized by their values of m/M. "Cloudy" regions indicate convective areas. Heavily hatched regions indicate where the nuclear energy generation (ε_H or ε_{He}) exceeds 10^3 erg g^{-1} s^{-1}. Regions of variable chemical composition are dotted. The letters $A \ldots K$ above the upper abscissa indicate the corresponding points in the evolutionary track, which is plotted in Fig. 31.2 (b). (After KIPPENHAHN et al., 1965)

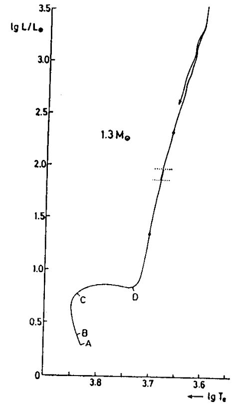


Fig. 32.2. The evolutionary track of a star of $1.3M_\odot$ with the initial composition $X_H = 0.9$, $X_{He} = 0.099$, $Z = 1 - X_H - X_{He} = 0.001$ as computed by THOMAS (1967). The letters $A - D$ refer to the corresponding evolutionary states in Fig. 32.3. The arrows indicate the direction of the evolution. This direction is reversed for a short period between the dotted horizontal lines. This transient drop in luminosity at about lg $L/L_\odot = 2$ occurs when the hydrogen-burning shell crosses the chemical discontinuity left behind when the bottom of the outer convective zone moves outwards again in the mass scale after it has reached its deepest extension (see Fig. 32.3)

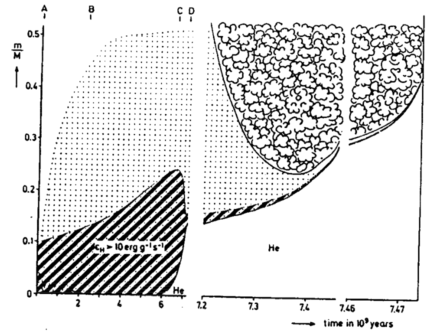


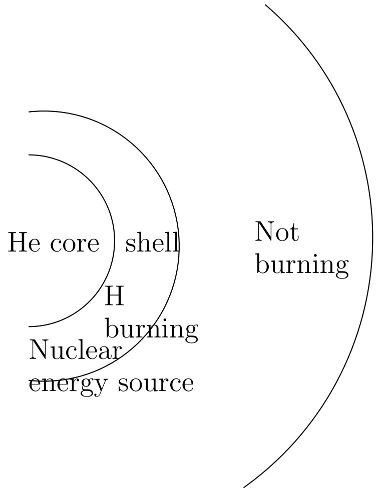
Fig. 32.3. The evolution of the internal structure of a star of $1.3M_\odot$ plotted in the same manner as in Fig. 31.2(a). The main region of hydrogen burning is hatched, "cloudy" areas indicate convection. Regions of variable hydrogen content are dotted. (After THOMAS, 1967)

314

24.6 Central Hydrogen depletion

$M > M_\odot$ first. Eventually the temperature does rise as X decreases until the fuel runs out in the core. When this happens the He core gravitationally contracts on t_{KH}. The B to C hook in the HR diagram called the Henyey hook is due to this. Contraction halts once hydrogen burning has ignited in a shell surrounding the helium core.

for $M < M_\odot$, T is rising even on the main sequence, so the transition to shell burning is more gradual. Since there is no convective core, there is no sudden depletion, the helium core just slowly grows. Can see this in the Kippenhahn diagrams, as the helium core ramps up at about 6 Gyr.



The helium core mass will be growing in time. Question is can this evolution persist until all H is burned. We will show that the above picture can only be constructed when the helium core is a small fraction of the mass.