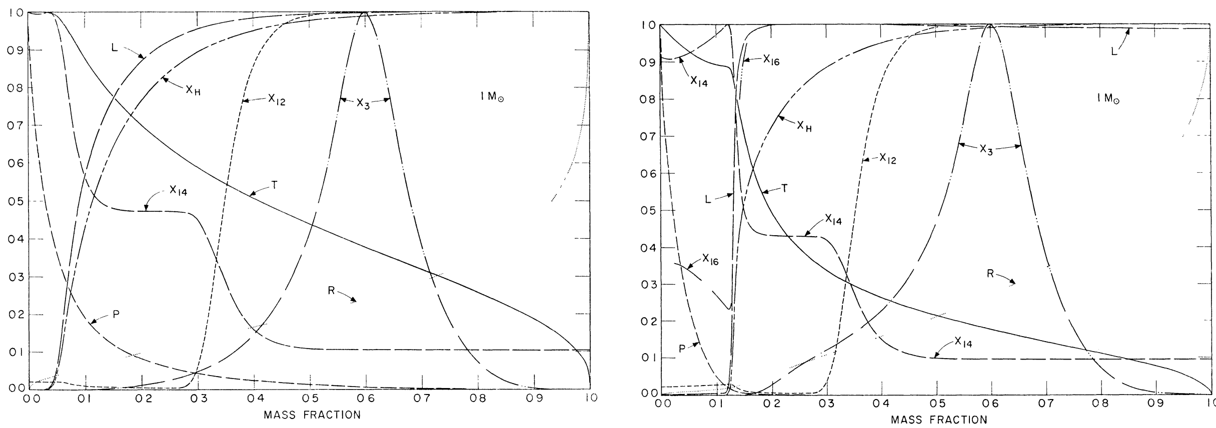

FIG 9.—The variation with mass fraction, for a 1 $M_\odot$ star, of state and composition variables when $t = 9.20150 \times 10^9$ yr. Variables have the same significance and units as in Fig. 8 In addition, pressure P is given in units of 10^{17} dyne/cm^2. Scale limits correspond to $0\,0 \le P \le 13\,146$, $0\,0 \le T \le 19.097$, $0\,0 \le L \le 2.1283$, $0.0 \le R \le 1.2681$, $0\,0 \le X_H \le 0\,708$, $0.0 \le X_3 \le 5.15 \times 10^{-3}$, $0.0 \le X_{12} \le 3\,61 \times 10^{-3}$, and $0.0 \le X_{14} \le 1.15 \times 10^{-2}$. Stellar radius is $R_s = 1\,3526\, R_\odot$, and central density (not shown) is 1026 0 gm/cm^3.

FIG. 10.—The variation with mass fraction, for a 1 $M_\odot$ star, of state and composition variables when $t = 10\,3059 \times 10^9$ yr Variables have the same significance and units as in Figs 8 and 9 In addition X_{16} = central abundance by mass of O^{16}. Scale limits correspond to $0\,0 \le P \le 415.15$, $0\,0 \le T \le 23.868$, $0\,0 \le L \le 2\,8227$, $0\,0 \le R \le 2.1334$, $0\,0 \le X_H \le 0\,708$, $0\,0 \le X_3 \le 5.35 \times 10^{-3}$, $0\,0 \le X_{12} \le 3.61 \times 10^{-3}$, $0\,0 \le X_{14} \le 1\,26 \times 10^{-2}$, and $0\,0 \le X_{16} \le 1\,08 \times 10^{-2}$. Stellar radius is $R_s = 2.2179\, R_\odot$, and central density (not shown) is 15214 gm/cm^3.

Figure 5.5: Interior properties of a $1M_\odot$ model. (Left) corresponds to point 5 in Figure 5.1, just after H is exhausted at center, for $t = 9.2 \times 10^9$ yr. $R = 1.35R_\odot$. (Right) corresponds to point 10 in Figure 5.1, when shell burning is thin, at $t = 10.3 \times 10^9$ yr. $R = 2.22R_\odot$. From Iben [1967a].

<u>**November 5**</u> ....

5.2.2 Low-mass stars

- Consider stars $M < 2.3M_\odot$.
- As H is finished at the center, we see the situation in Figure 5.5(a).
- The He core grows gradually and the star remains below the C-S limit, unlike the high-mass case.
- The density is also higher and so there is a degenerate component.
- The degeneracy provides enough pressure so that core contraction is not as extreme as for higher-mass stars.
- The hydrogen-burning shell is defined as the width of the region where the luminosity increases.
- In Figure 5.5(b), we see that it is quite narrow.
- Also seen is a dip in L in outer layers, where the envelope is expanding
- The star moves up the RGB, Figure 5.6.
- As always, from homology we learned that luminosity must increase as μ increases in the core.
- A strong degeneracy is clear in the core pressure profile.
- A convective envelope has developed down to about $0.29M$, reflected in the sharp change in $X_{\rm H}$.
- This is also evident in Figure 5.7, after point D.
- The convection mixes material from the surface to a point that once produced He from H. When it reaches its deepest extent, this is the *first dredge up*. What happens?
  - The surface He abundance increases, and ^{3}He and CNO elements get mixed in.
  - A doubling of the surface ^{14}N abundance.

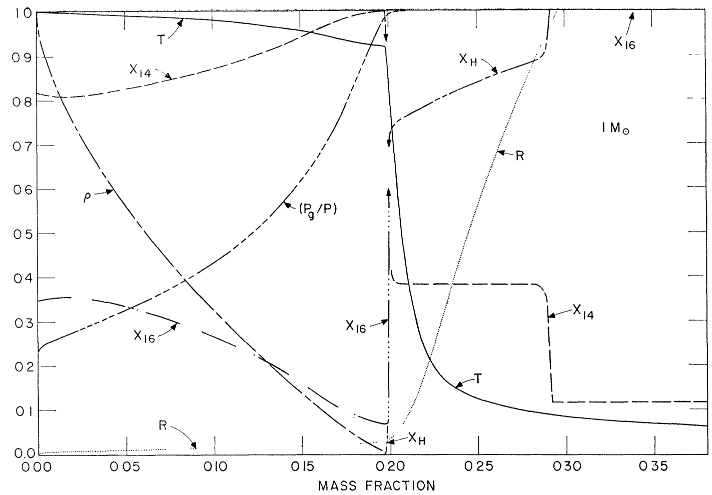

FIG 11 —The variation with mass fraction, for a 1 $M_\odot$ star, of state and composition variables when $t = 10\,8747 \times 10^9$ yr Variables have the same significance and units as in Figs 8–10. Scale limits correspond to $0.0 < \rho < 91171$, $0\,0 \le T \le 27\,351$, $0\,0 \le L \le 11.422$, $0.0 \le R \le 1$, $0\,0 \le X_H \le 0\,693$, $0\,0 \le X_{14} \le 1.41 \times 10^{-2}$, and $0\,0 \le X_{16} \le 1\,08 \times 10^{-2}$. Stellar radius is $R_s = 6\,1784\,R_\odot$, and central pressure (not shown) is $6552\,2 \times 10^{17}$ dyne/cm^2 Finally, the ratio of pressure computed in the perfect-gas approximation to the actual pressure with degeneracy included is given by P_g/P and scale limits correspond to $0\,0 \le P_g/P \le 1\,0$.

Figure 5.6: Corresponds to point 13 in Figure 5.1, at $t = 10.87 \times 10^9$ yr. The radius $R = 6.18 R_\odot$. From Iben [1967a].

  - A reduction of ^{12}C by about 30%.
  - Formation of ^{12}C/^{13}C of about 20-30.
  - A reduction of surface lithium and berrylium abundances by a few orders of magnitude.

- See Figure 5.8 for an illustration.
- Because of degeneracy, the core is dominated by heating by contraction, since the thermal energy of degenerate electrons is independent of temperature.
- The H-burning shell continues to move outwards into fresh hydrogen layers.
- The convection zone retreats, leaving behind a chemical discontinuity.
- When the shell reaches this area, the RGB motion briefly goes down due to a decrease in H burning because of the lower mean molecular weight.
- After it crosses the discontinuity, the mean molecular weight is again constant and the luminosity increases again.
- Therefore, the star crosses the same luminosity point 3 times, increasing star counts at this level.
- This is the *RGB luminosity bump*, and represents about 20% of the RGB lifetime.
- Along the RGB, the core is becoming denser and denser, and some gravitational energy is being produced.
- However, there are some substantial energy losses due to neutrino production, and sometimes these can be greater than the gravitational energy release.
  - There are potentially 3 neutrino production mechanisms.
  - Pair annihilation processes are when high-energy photons produce electron-positron pairs, that annihilate and produce photons again, or, rarely, a neutrino-anti neutrino pair. This typically only happens above one billion degrees.

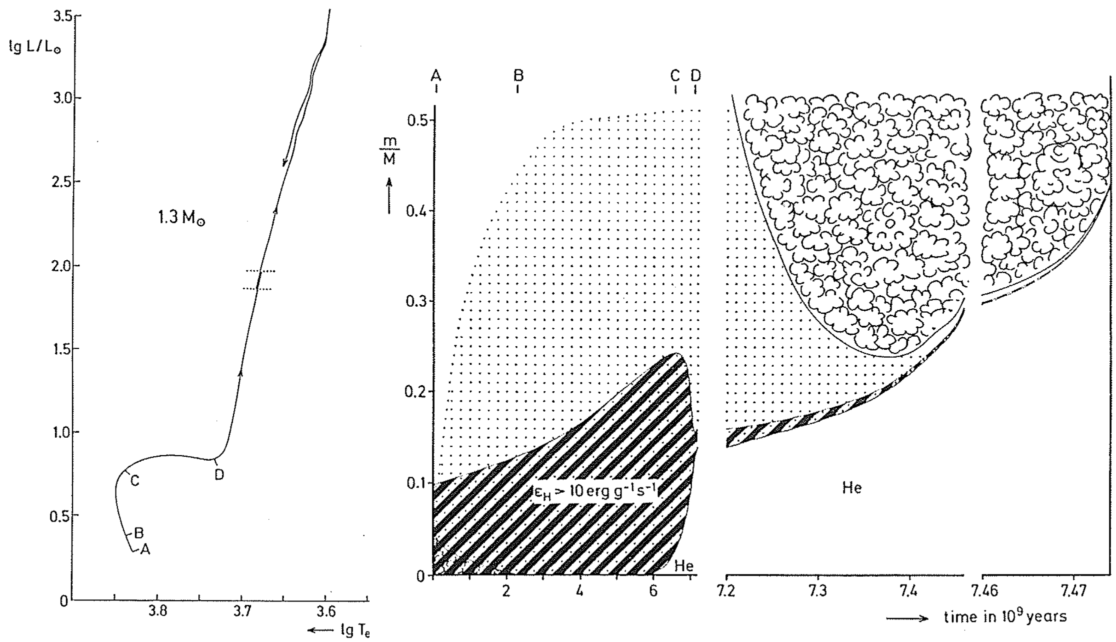

Figure 5.7: Evolution of a $1.3M_{\odot}$ star. On the left, the horizontal dashed regions denote the luminosity bump location. On the right, main regions of H burning are hatched, convection is cloudy, and variable hydrogen content is dotted. From Kippenhahn and Weigert [1990].

- Photoneutrino processes from Compton scattering (electron + photon), when the photon becomes a neutrino-anti neutrino pair.
- Plasma processes when the photon traveling in a dense, degenerate environment becomes like a plasmon (having mass) and decays into a neutrino-anti neutrino pair.

- This can lead to the $\mathrm{d}L/\mathrm{d}m = \varepsilon < 0$ in the innermost regions.
- The maximum temperature is now located off center, in a shell.
- Another cooling process is due to conduction from the degnerate electrons.
- In any case, the maximum temperature, wherever it is located, is increasing as time goes on because of the increasing He core mass and gravitational heating up of the inner layers.

Helium flash

- So the temperature of the burning shell is increasing up the RGB, and when it reaches 10^8K, the *helium flash* occurs.
- In a more massive star, the release of energy by nucelar burning would cause an increase in pressure and an expansion of material (core), and then cooling and an equilibrium would be restored, all rather smoothly.
- In the degenerate case, however, the gas pressure is basically independent of temperature (recall the EOS), and the high temperature causes no immediate reaction at the core.
- Instead the nuclear energy generation increases → higher temperatures → increased energy generation, . . .
- This is called a thermal runaway.

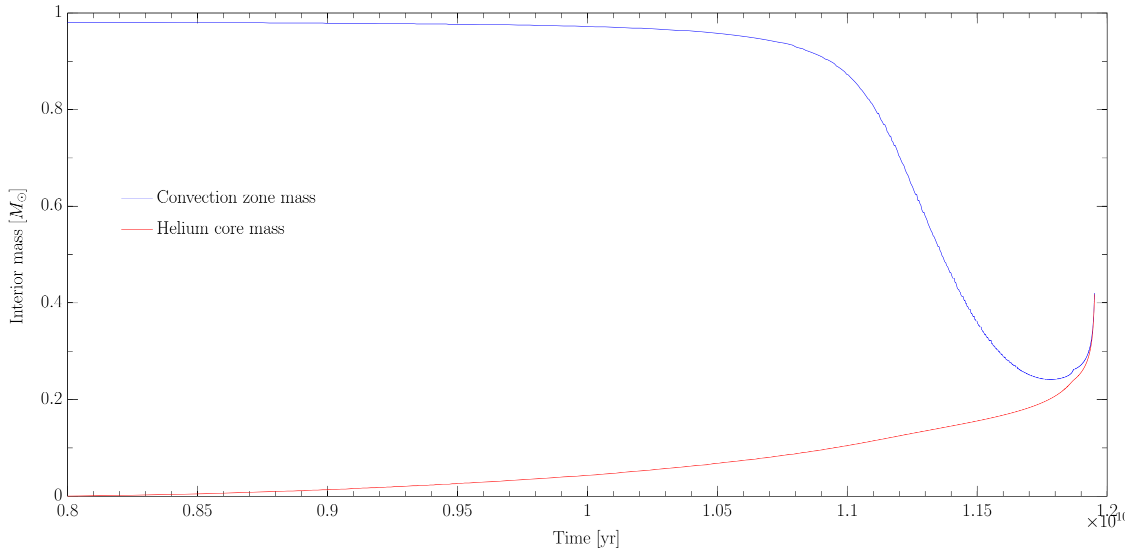

Figure 5.8: How the base of the convection zone and the mass of the He core change with time for a $1M_\odot$ model. This illustrates how the first dredge up occurs.

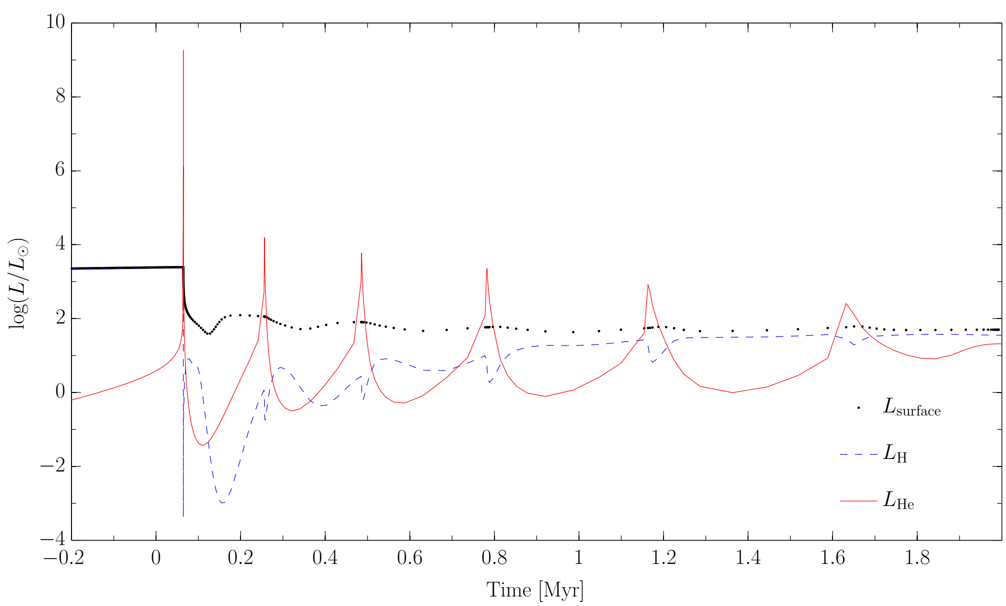

Figure 5.9: Helium flash for a $1M_\odot$ model. Time has been shifted to approximately the start of the flash, which corresponded to about 12 billion years.

- The local luminosity in the core increases to about 100 billion $L_\odot$ in a few hours!
- See Figure 5.9.
- The does not make it to the surface, however, but is absorbed by the overlying layers, which expand just outside the He-burning shell.
- Convection also sets in which spreads out the energy production over more mass layers.
- Eventually, the temperature gets so high that degeneracy is "lifted" at the point where the flash occurs. Recall Equation (2.63):
$$\frac{\rho}{\mu_\mathrm{e}} > 2.4 \times 10^{-8} T^{3/2}.$$
- Interior to this, some smaller flashes may take place which eventually removes the degeneracy everywhere.
- After this, the core expands (envelope contracts!) and cools, and an equilibrium of helium burning in the core proceeds.
- The dynamical time scale of the star, because it is so large, is of the order of months.
- So the He flash in the core is not visible at the surface. The whole process takes on the order of one million years.
- It is now on the *helium burning main sequence*, or better, the *horizontal branch*.
- The future evolution from now on follows roughly what a higher-mass star will be.