Figure 5.5: The internal evolution of a $5M_\odot$ star. Note the growing shell-burning size with time. Cloudy areas indicate convection zone. Hatched regions are for strong nuclear burning regions. Dotted regions are for variable chemical composition. From Kippenhahn and Weigert [1990].

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- Continuing on, between 6 and 7, the convective envelope increases its extent in depth, carrying the luminosity to the surface, as the core keeps contracting and the star keeps getting bigger.

- The convection almost reaches the burning shell, but mixes the star and creates interesting abundance ratios for observers.

- A small convective core sets in with N being converted to O (recall one of the intermediate reactions in the CNO cycle).

- When point 7 is reached, the central temperature and density are such that He burning via the triple-alpha process takes place.

- This occurs at about $T = 10^8$K.

- Now, instead of gravitational contraction in the core, nuclear energy again can support the star.

- It is a rapid increase in enery such that it causes the core to expland (energy can't get carried out fast enough).

- There is still shell burning that is supplying most of the stellar luminosity, but it slows down a bit, and the luminosity decreases abruptly.

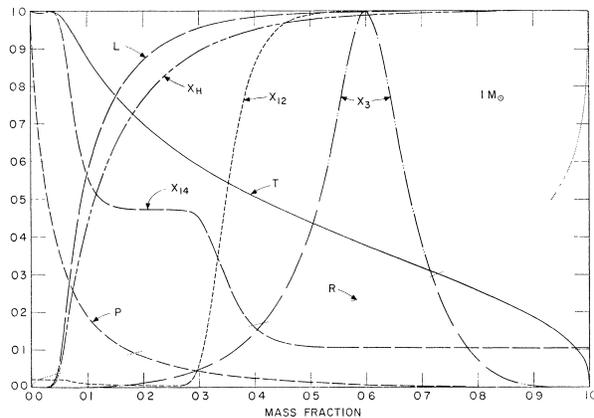- Because of the shell-burning law too, the expanding core causes a shrinking star.

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/cm². Scale limits correspond to $0.0 \leq P \leq 13\,146$, $0.0 \leq T \leq 19.097$, $0.0 \leq L \leq 2.1283$, $0.0 \leq R \leq 1.2681$, $0.0 \leq X_H \leq 0.708$, $0.0 \leq X_3 \leq 5.15 \times 10^{-3}$, $0.0 \leq X_{12} \leq 3.61 \times 10^{-3}$, and $0.0 \leq X_{14} \leq 1.15 \times 10^{-2}$. Stellar radius is $R_s = 1.3526$ $R\odot$, and central density (not shown) is 1026.0 gm/cm³.
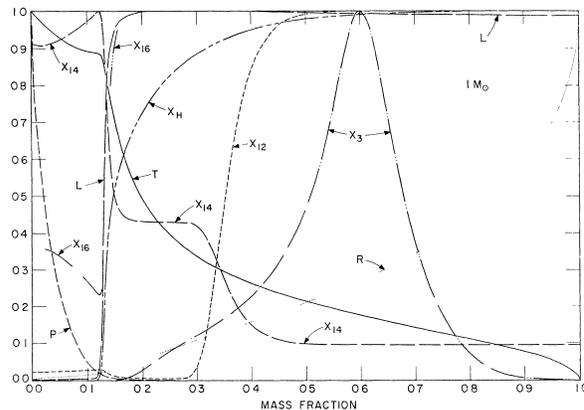
FIG. 10.—The variation with mass fraction, for a 1 $M\odot$ star, of state and composition variables when $t = 10.3059 \times 10^9$ yr Variables have the same significance and units as in Figs 8 and 9 In addition X_{16} = central abundance by mass of O¹⁶. Scale limits correspond to $0.0 \leq P \leq 415.15$, $0.0 \leq T \leq 23.868$, $0.0 \leq L \leq 2.8227$, $0.0 \leq R \leq 2.1334$, $0.0 \leq X_H \leq 0.708$, $0.0 \leq X_3 \leq 5.35 \times 10^{-3}$, $0.0 \leq X_{12} \leq 3.61 \times 10^{-3}$, $0.0 \leq X_{14} \leq 1.26 \times 10^{-2}$, and $0.0 \leq X_{16} \leq 1.08 \times 10^{-3}$. Stellar radius is $R_s = 2.2179$ $R\odot$, and central density (not shown) is 15214 gm/cm³.

Figure 5.6: 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].

- After point 7 the star follows a similar path as if it were on the Hayashi track, toward higher temperatures.

- For increasing total stellar mass, the core contracts faster and the He-burning temperature is reached faster, so RG lifetime decreases with mass.

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 5.6(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 5.6(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 5.7.

- 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_H.

- This is also evident in Figure 5.8, 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?
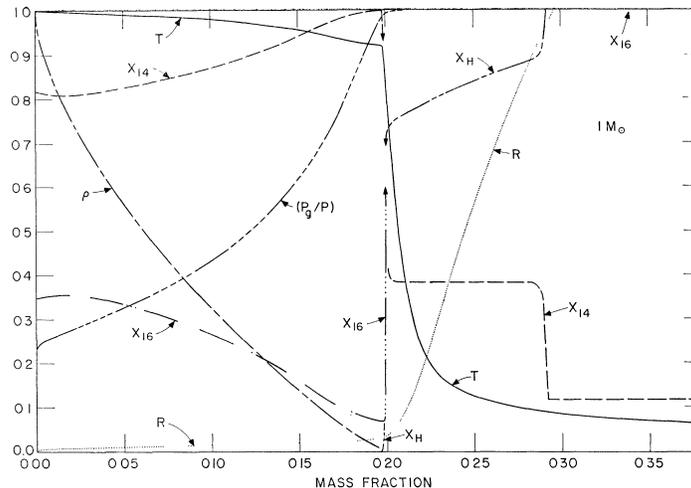
Fig 11 —The variation with mass fraction, for a 1 $M_\odot$ star, of state and composition variables when $t = 10\,8747 \times 10^9$ yr Variables have the same significance and units as in Figs 8–10. Scale limits correspond to $0.0 < \rho < 91171$, $0\,0 \leq T \leq 27\,351$, $0\,0 \leq L \leq 11.422$, $0.0 \leq R \leq 1$, $0\,0 \leq X_H \leq 0\,693$, $0\,0 \leq X_{14} \leq 1.41 \times 10^{-2}$, and $0\,0 \leq X_{16} \leq 1\,08 \times 10^{-2}$. Stellar radius is $R_s = 6\,1784\,R_\odot$, and central pressure (not shown) is $6552\,2 \times 10^{17}$ dyne/cm² 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 $0\,0 \leq P_g/P \leq 1\,0$.

Figure 5.7: 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].

- The surface He abundance increases, and ^{3}He and CNO elements get mixed in.
- A doubling of the surface ^{14}N abundance.
- 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 5.9 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.

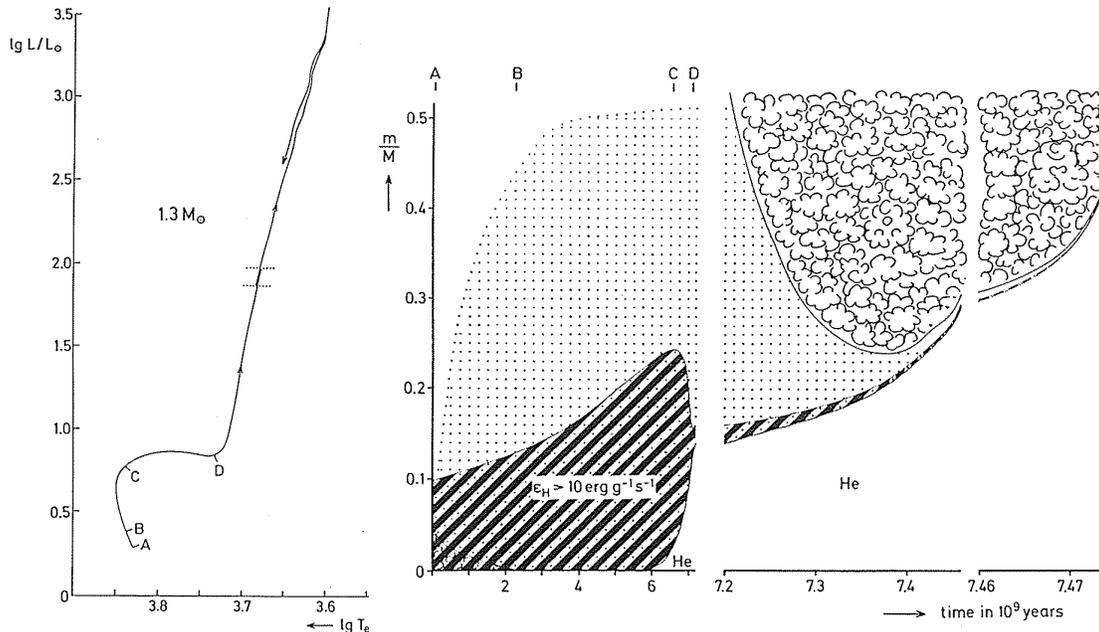- There are potentially 3 neutrino production mechanisms.

Figure 5.8: Evolution of a $1.3 M_\odot$ 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].

- – 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.

- – 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 $dL/dm = \varepsilon < 0$ 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.