Unit 21

Towards and up the Red-Giant Branch

21.1 High-mass stars

- The red-giant branch (RGB) for the 7 $M_\odot$ star is approximately models 1500-1750.
- As the star approaches the bottom of the RGB, opacities increase because of the cooling outer layers, and a convection zone near the surface appears. See 7Ma-1500 in the "Kippenhahn" panel.
- Mixing occurs near the surface.
- H^- is the dominant opacity source.
- As the effective temperature continues to decrease, the luminosity finally begins to increase as convection allows the luminosity to escape more readily.
- The shell burning power increases, but at the same time the mass in the shell decreases.
- The variation in the luminosity is interesting, as you can see that most of it is generated in a thin shell at about $m \approx 1.1\ M_\odot$ in 7Mb-1530 in the "Summary Profile" panel.
- But note that near the center there is a small amount due to initial He burning that is beginning to take place. See the "Power" panel and the "text" panel.
- The subtle decrease in L in the envelope is due to expansion of the outer envelope where no nuclear sources reside and gravitational energy is "lost."
- Note the core is no longer isothermal as a temperature gradient is required to carry out the luminosity supplied by He burning ("Summary Burn" panel).
- Continuing on, 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 at model 1600, 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 around model 1800 is reached, the central temperature and density are such that He burning via the triple-alpha process takes place and is steady.

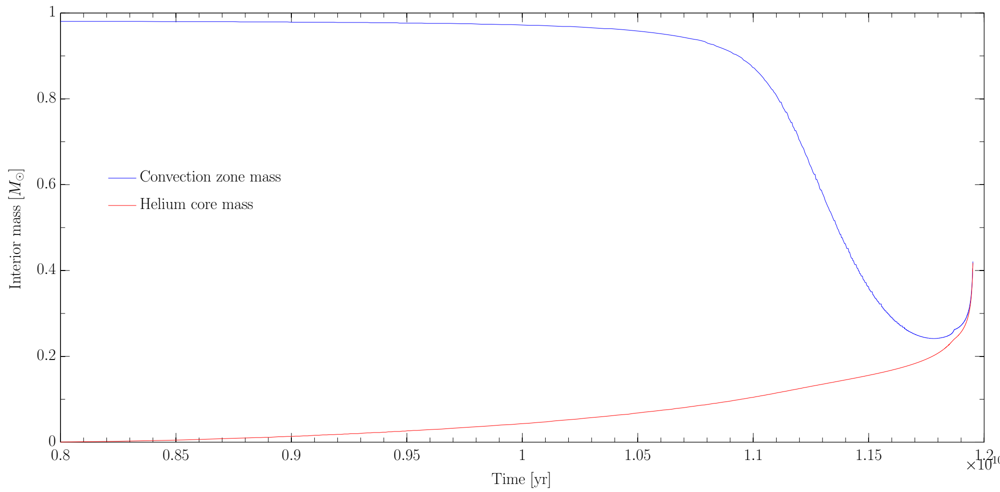

Figure 21.1: How the base of the convection zone and the mass of the He core change with time for a $1M_\odot$ model. This illustrates how the first dredge up occurs.

- This occurs at about $T = 10^8$K.
- Now, instead of gravitational contraction in the core, nuclear energy again can support the star.
- The star "leaves" the RGB.
- 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.

21.1.1 Low-mass stars

- The RGB phase for the low-mass star is models 330 to 4500. There are many more short time steps in this case because of the degenerate condition in the core.
- The He core stars 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 strong degeneracy is clear in the "temperature-density" panel.
- A convective envelope develops down to about $0.2M$, and results in a sharp change in $X_{\rm H}$ ("summary profile" panel).
- 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.
  - A reduction of ^{12}C by about 30%.

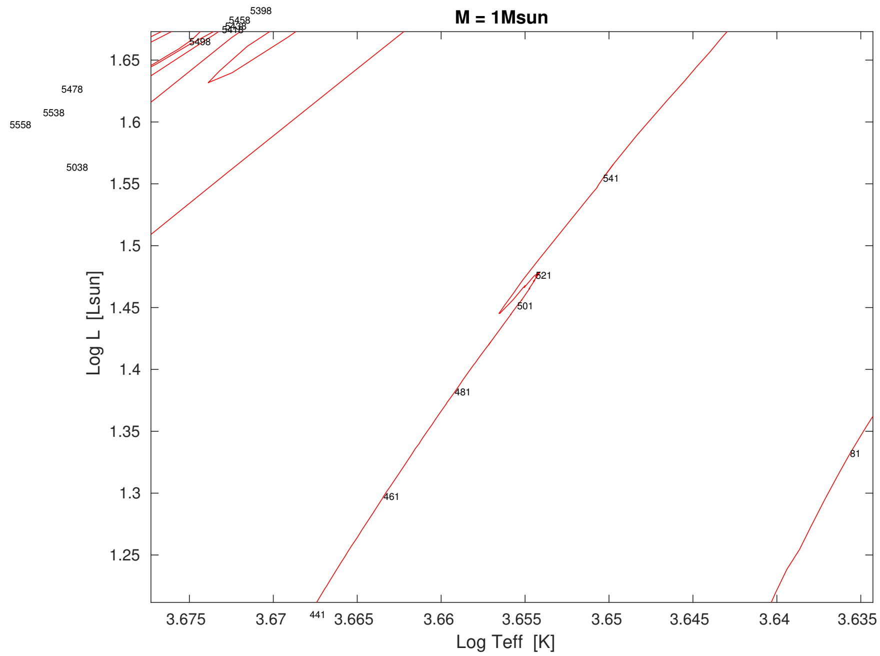

Figure 21.2: A zoom in on the H-R track of the 1 $M_\odot$ model during the RGB luminosity bump. The model numbers are annotated.

- Formation of $^{12}C/^{13}C$ of about 20-30.
- A reduction of surface lithium and berrylium abundances by a few orders of magnitude.
- Some of these can be seen in the "abundance" panel as the deep mixing occurs.

- See Figure 21.1 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 (see 1Ma-515 in the "H-R" panel)
- 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.
- A zoom of this is shown in Figure 21.2.
- 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 that don't involve nuclear processes:

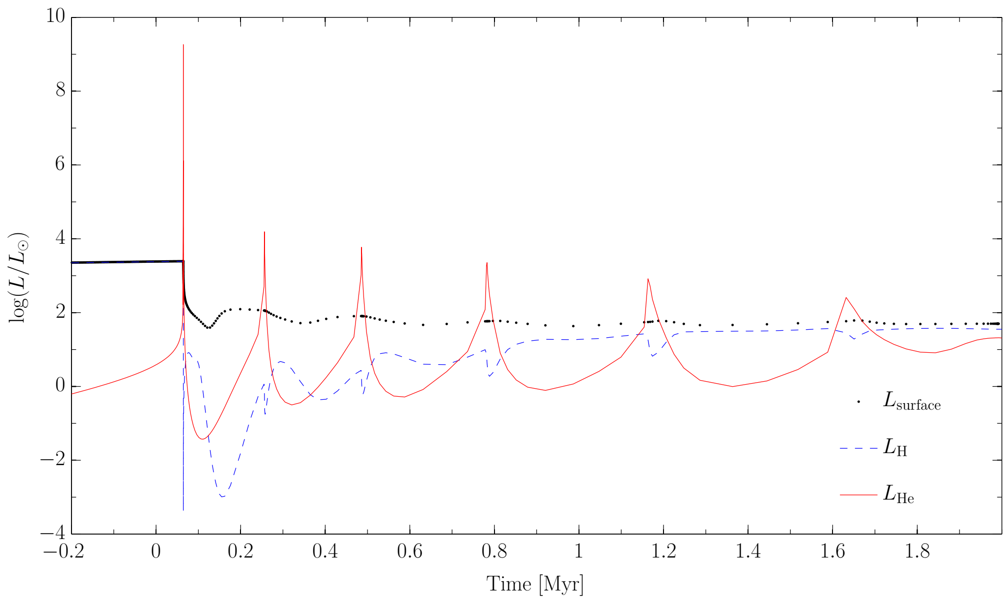

Figure 21.3: Helium flash for a $1M_\odot$ model. Time has been shifted to approximately the start of the flash, which corresponded to about 12 billion years. Note the decrease in the surface luminosity due to the expansion of the He core and cooling of H-burning shell.

  - 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 $\mathrm{d}L/\mathrm{d}m = \varepsilon < 0$ in the innermost regions.
- The maximum temperature is now located off center, in a shell. See 1Mb-3000 in the "summary burn" panel.
- 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.

21.2 Helium flash

- The He flash occurs after model 4000 or so.
- The temperature of the burning shell is increasing up the RGB, and when it reaches 10^8K, the *helium flash* occurs.
- It coincides when the He-core mass is about 0.5 $M_\odot$ (about 0.46 in our case), mostly independent of the total stellar mass.
- In a more massive star (which would be non-degenerate matter), 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.
- The local luminosity in the core increases to about 100 billion $L_\odot$ in a few hours! 1Ma-4300 in the "kippenhahn" panel shows the luminosity increase.
- See Figure 21.3.
- The new luminosity does not make it to the surface, however, but is absorbed by the overlying layers, which expand just outside the H-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 (density is roughly constant). Recall Equation (8.8):

$$\frac{\rho}{\mu_{\rm e}} > 2.4 \times 10^{-8} T^{3/2}.$$

- Interior to this first outer layer explosion, some smaller flashes may take place which eventually removes the degeneracy everywhere. This is seen well around 1Ma-5650 in the "temperature-density" panel, where the degeneracy is removed.
- 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.
- See Figure 21.3 again.
- It is now on the *helium burning main sequence*, or better, the *horizontal branch*, or for seismologists, the *red clump*.