Unit 24

Asymptotic Giant Branch

24.1 General overview

- The models representing the AGB for the 1 $M_\odot$ star are approximately 5750-6000.
- The models representing the AGB for the 7 $M_\odot$ star are approximately 2260-2495, although the full AGB evolution was not computed.
- The H-R tracks are shown in Figure 24.1
- To summarize the approach to the AGB after horizontal branch evolution, the main driver is that helium is less and less available for fusion in the core.
- As C and O builds up in the core, the mean molecular weight increases.
- The core contracts and increases in temperature (as before, in the Hertzsprung Gap).
- The contracting core releases gravitational energy and some gets converted to thermal energy and it reignites He in a shell around the core.
- The shell-burning law kicks in and the envelope expands, star moves to the red.
- There are 3 main characteristics of the AGB:
  1. Nuclear burning takes place in 2 shells (with an He layer in between). As He burning in the core exhausts, a new shell of He burning takes over in addition to the H-burning shell.
  2. The luminosity is determined by the core C-O mass only.
  3. A strong stellar wind due to radiation pressure develops causing significant mass loss.
  4. s-process elements are produced.
- Let's look at some of these.

24.2 Double-shell burning

- Some important interior profiles of the 7 $M_\odot$ star on the AGB during double-shell burning are shown in Figure 24.2.
- The 2 burning shells are evident from the $\varepsilon_{\rm nuc}$.

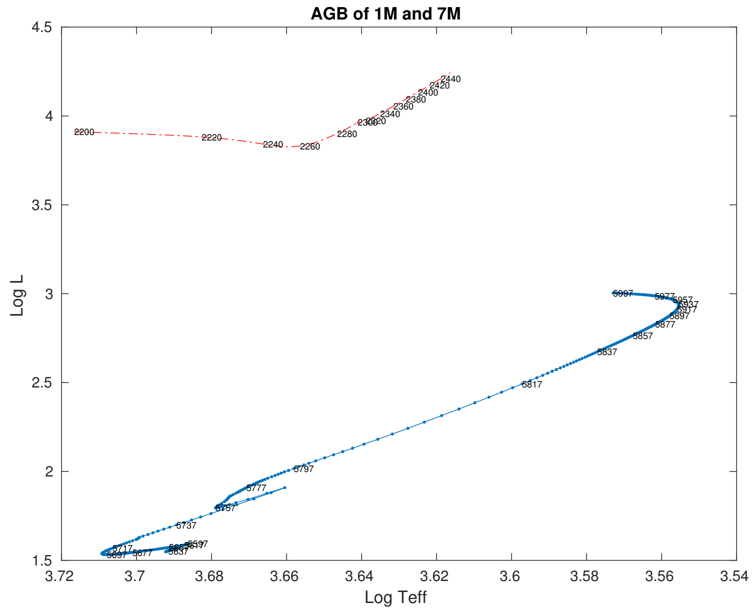

Figure 24.1: Zoom of the asymptotic giant branch of the $1\ M_\odot$ star (blue) and $7\ M_\odot$ star (red).

- The luminosity is interesting and notable: Remember that $\mathrm{d}L/\mathrm{d}m = 0$ unless energy is being generated, so here we'd really have to account for $\varepsilon_{\rm nuc} + \varepsilon_{\rm grav}$.
- The finite luminosity at the innermost region is from gravitational contraction of the core, as $\varepsilon_{\rm grav} > 0$.
- Between the 2 shells, the luminosity is decreasing slightly as that region expands (does work against gravity), and $\varepsilon_{\rm grav} < 0$.
- In the outer part above the H shell, the envelope is also contracting, releasing gravitational energy.
- This is the shell-burning law in triple!

24.3 AGB evolution

- The core is too cold for C or O to burn (neutrinos are cooling it!). See 7Ma-2425 in the "kippenhahn" panel.
- Furthermore, for stars lower than about $10\ M_\odot$, the carbon-oxygen core becomes degenerate (our models do not get to that point).
- Thus, the contracting core does not heat up the gas and the high internal temperatures needed to ignite the core are not reached.
- As the star reaches point continues, the shell-burning law has the core contracting (increasing in mass), the inner shell expanding, and the outer envelope contracting and increasing in effective temperature.
- But now the region between the two shell-burning sources has expanded sufficiently so that the temperature in the outer H-burning shell drops and extinguishes.
- Now there are only 2 distinct regions: the contracting core, and the now expanding envelope with He burning in between (shell-burning law).
- Figure 24.2 (bottom panel) shows this.

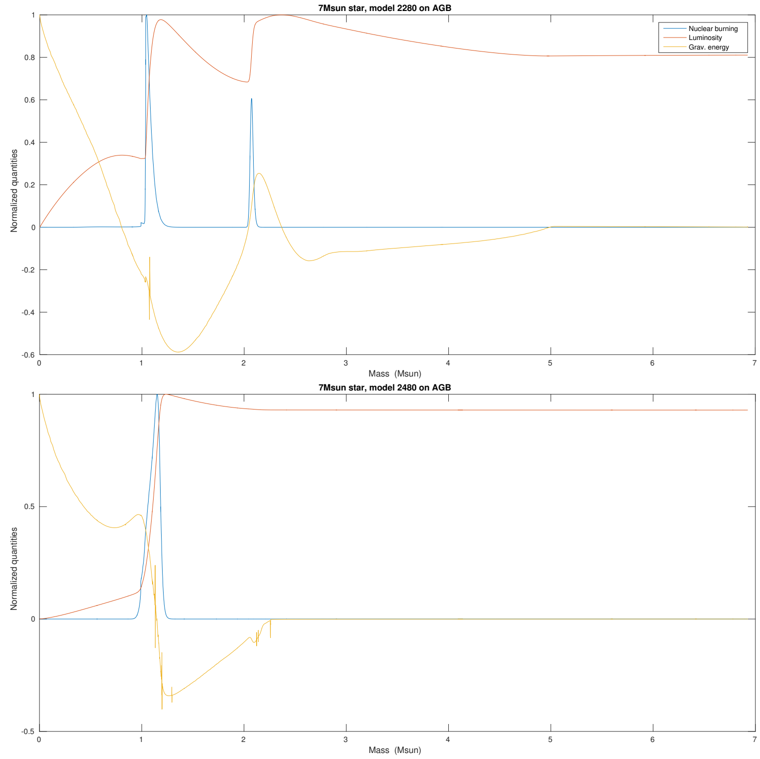

Figure 24.2: Interior profiles of the 7 $M_{\odot}$ star on the AGB during double-shell burning. The bottom panel is at a later stage when the outer-shell burning is extinguished.

- The luminosity increases as the CO core mass increases and contracts, and the star keeps climbing the AGB.
- A convective surface region develops (cooler surface temperature) and extends deeply, and "dredges up" processed material.
- It reaches down to the regions where the H shell had been burning for a while.
- Low-mass stars don't typically have a second dredge up since their H shell burning continues strongly.
- This dredge up brings a lot of material to the surface and reduces the mass size of the H-exhausted region.
- This is one reason why very massive white dwarfs are not formed.

24.4 Thermal pulses

- The following applies mostly for stars below 5 $M_{\odot}$.
- One sees that the growing He-burning shell approaches the bottom of the H-rich envelope.
- The He burning dies down a bit when it hits this region, contracts rapidly, and a H-shell reignites.
  1. As H burns, the He ashes fall onto the former shell burning region, and are compressed and heated.
  2. When the mass reaches about $10^{-3} M_{\odot}$ for a CO core mass of about $0.8 M_{\odot}$, He ignites again.
  3. A runaway occurs, in that this ignition heats the overlying shell burning region and causes it to burn even more violently (note the temp. dependence of nuclear reactions).

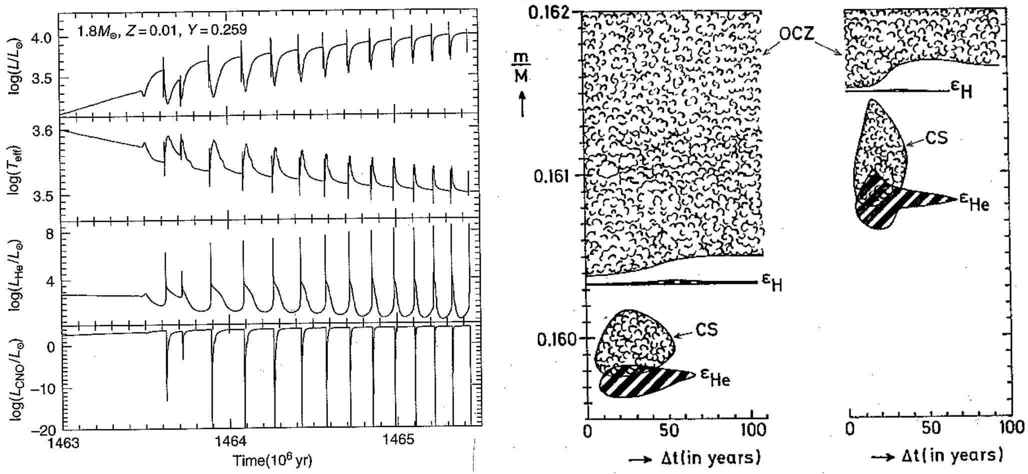

Figure 24.3: Thermal pulses. The left is for a $1.8M_{\odot}$ model showing many pulses with time. The right is for a $5M_{\odot}$ model

4. The luminosity of the He burning reaches very high values, and this causes the layers above it to expand.
5. The H-burning shell turns off.
6. Because of the high luminosity, a convection zone develops above the He-burning shell.
7. Eventually the convection helps expand the region, and the He burning drops strongly and cools.
8. The convection zone disappears as the luminosity decreases.
9. He burning continues, using up the He that the H-burning region produced before the flash.
10. As this source reaches the new discontinuity, a new H-burning region is created as before.
11. The He ash falls onto the He layer and the whole process happens again, now at a higher position.

- The timescale between pulses can be approximated roughly by

$$\log \tau \approx 3 + 4.5(1 - M_c/M_{\odot}). \tag{24.1}$$

- For a core mass of $0.5M_{\odot}$, this gives about 10^5 years; but drops to about 10 years for near-critical mass stars.
- Some stars can go through hundreds of pulses before the H shell gets depleted.
- In higher-mass stars, these cannot be observed because they are buried within the massive envelope.
- In low-mass AGB stars, the effects of the pulses can be seen chemically.
  - In the pulses when H burning is turned off, the surface convection zone moves inward, and a third dredge up can occur.
  - This can bring up carbon and heavy *s* elements (Sr, Y, Zr, Ba, La, Ce, Pr, Nd). Carbon-rich stars can be "produced."
  - Stars below about $1.5M_{\odot}$ will likely not go through a third dredge up, as their envelope mass isn't large enough.
  - For more massive stars, large amounts of lithium can be produced (from berrylium 7) and brought to the surface.

24.5 Production of s elements

- As mentioned earlier, AGB stars are spectroscopically enriched in s-process elements.
- The s refers to *slow* neutron captures (compared to β decay).
- About half of the elements heavier than Fe are created by this process.
- You need neutrons to make these heavier elements, where the neutron eventually decays into a proton to make a stabler isotope.
- The neutrons densities needed are lowish, of order $10v$ per unit volume.
- Since at this stage there is a large abundance of N-14 in the intershell region, it gets converted to Ne by
$$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}(\beta^+,\nu)^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}. \tag{24.2}$$
- If the temperatures at the base of the intershell region get to a few hundreds of MK, then $^{22}\mathrm{Ne}(\alpha,\mathrm{n})^{25}\mathrm{Mg}$ can provide a source of neutrons.
- For stars of initial mass $< 3M_\odot$, it probably does not get hot enough for this reaction to occur.
- There may be some channels through carbon 13 that provide a high neutron density for low-mass AGB stars.
- However, this is still a very active area of research due to many physical uncertainties.