Evolution onto the Asymptotic Giant Branch

When a star on the horizontal branch[1]eventually runs out of helium fuel in its core, it begins another series of dramatic changes. Much as it did during the red giant branch, it evolves along a mostly vertical path in the Hertzsprung-Russell diagram toward large radii and luminosities but low effective temperatures (see Fig. 1). This phase of evolution is known as the *asymptotic giant branch* (AGB).

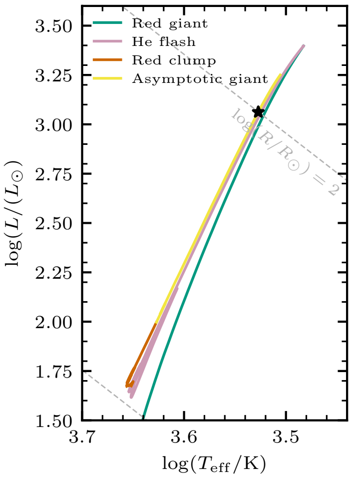

Figure 1: Evolutionary track in the Hertzsprung-Russell diagram for a *MESA* model of the Sun, spanning the RGB phase through to the AGB. The asterisk marks the case plotted in Fig. 2.

Structure on the AGB

The internal structure of a star during the AGB phase shares many similarities with its structure during the earlier RGB phase. Most importantly, the star once again exhibits a pronounced dichotomy between core and envelope; a massive, dense radiative core, spanning only a small fraction of the star's radius, is surrounded by a low-density convective envelope (see Fig. 2).

One significant difference from the RGB phase, however, is the composition of the core. Unlike the almost-pure helium cores encountered on the RGB, the core of AGB stars are composed of a mixture of carbon and oxygen. The carbon is produced by the triple alpha reaction during the earlier core helium burning, as discussed in *Handout* xxiv. The oxygen results from alpha capture onto carbon,

$$\underbrace{{}^{12}\mathrm{C} + 6e^-}_{\text{carbon-12 atom}} + \underbrace{{}^{4}\mathrm{He} + 2e^-}_{\text{helium-4 atom}} \longrightarrow \underbrace{{}^{16}\mathrm{O} + 8e^-}_{\text{oxygen-16 atom}} + \underbrace{\gamma}_{\text{energy}}, \qquad (1)$$

which out-competes the triple alpha reaction toward the end of the core helium burning.

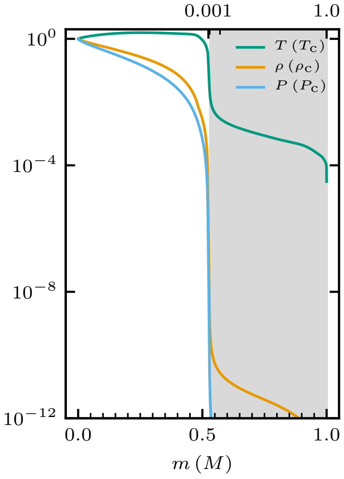

Figure 2: The temperature T, density ρ and pressure P (in units of their central values $T_{\rm c} = 1.09 \times 10^8\,{\rm K}$, $\rho_{\rm c} = 1.07 \times 10^6\,{\rm g\,cm^{-2}}$, $P_{\rm c} = 2.94 \times 10^{22}\,{\rm dyn\,cm^{-2}}$), plotted as a function of interior mass m for a *MESA* model of the Sun at a luminosity $R = 100\,{\rm R}_\odot$ on the RGB. The tick marks at the top indicate the position of layers with radial coordinates $r = 0.001, 0.01, 0.1$ and $1\,R$. Light-grey shading indicates convection. Compare against Fig. 2 of *Handout* xxii.

Double-Shell Energy Generation

Stars on the AGB generate energy in a pair of shells: an inner helium-burning shell, and an outer hydrogen-burning shell. These shells are sandwiched between the hydrogen-rich envelope and the carbon-oxygen core; and between the shells themselves is a narrow helium layer. The hydrogen-burning shell adds fresh helium to the top of this layer, and the helium-burning shell eats into the bottom of the layer. As a star ascends the AGB, both shells move outward to larger interior masses.

The Slow Neutron Capture Process

The AGB is an important phase of *stellar nucleosynthesis* — the process by which stars manufacture elements heavier than hydrogen,

[1] Or the red clump, if the star has a metallicity $Z \gtrsim 0.002$; see *Handout* xxiv.

helium and lithium (the three elements created in the Big Bang). If some kind of mixing brings fresh hydrogen into the helium layer between the shells, then carbon-13 produced during the CNO cycle[2] will undergo alpha capture to produce oxygen and a neutron:

$$\underbrace{{}^{13}\mathrm{C} + 6e^-}_{\text{carbon-13 atom}} + \underbrace{{}^{4}\mathrm{He} + 2e^-}_{\text{helium-4 atom}} \longrightarrow \underbrace{{}^{16}\mathrm{O} + 8e^-}_{\text{oxygen-16 atom}} + \underbrace{n}_{\text{neutron}} . \tag{2}$$

Because it is not affected by Coulomb forces, the neutron can easily be captured by other nuclei. It is through this process of *neutron capture* that all of the elements heavier than iron-56 are manufactured inside stars[3]. Neutron capture by iron-56 leads to the creation of successively heavier isotopes of iron; in shorthand form,

$${}^{56}\mathrm{Fe}\,(n,\gamma)\,{}^{57}\mathrm{Fe}\,(n,\gamma){}^{58}\mathrm{Fe}\,(n,\gamma){}^{59}\mathrm{Fe}. \tag{3}$$

Unlike the lighter isotopes, iron-59 is radioactive, decaying to cobalt-59 via emission of a β particle:

$${}^{59}\mathrm{Fe}\,(\cdot, e^-)\,{}^{59}\mathrm{Co} \tag{4}$$

(to conserve lepton number, an electron antineutrino is also produced in this reaction). This reaction is relatively slow, with a half-life of 44.5 d; however, the neutron production reaction (2) is even slower, and so there is a very low probability of the iron-59 capturing another neutron before it decays. This kind of neutron capture — where radioactive elements always decay before capturing another neutron — is known as *slow* or *s-process* capture, and is characteristic of AGB stars.

After the decay to cobalt-59, which is stable, the neutron capture proceeds again. As shown in the top panel of Fig. 3, the first few steps beyond cobalt-59 are as follows:

$${}^{59}\mathrm{Co}\,(n,\gamma)\,{}^{60}\mathrm{Co}\,(\cdot, e^-){}^{60}\mathrm{Ni}\,(n,\gamma){}^{61}\mathrm{Ni}\,(n,\gamma){}^{62}\mathrm{Ni}\ldots \tag{5}$$

Through a sequence of neutron captures and radioactive decays, the s-process builds elements all the way up to bismuth-209, the heaviest stable element[4] An additional neutron capture leads to the production of polonium-210, which decays via α emission back to lead-206 (see the lower panel of Fig. 3). Thus, the s-process cannot proceed any further.

Further Reading

Kippenhahn, Weigert & Weiss, §18.6,34; *Ostlie & Carroll*, §13.2; *Prialnik*, §9.6.

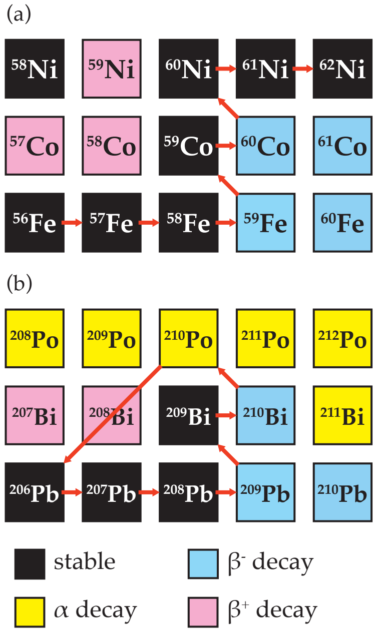

Figure 3: Nuclide charts (with atomic number increasing upward, and neutron number increasing rightward) for the start (a) and end (b) of s-process neutron capture in AGB stars. Isotopes are colored according to their principal decay mode. Neutron captures correspond to the right-pointing arrows; β emission to the up-left arrows; and α emission to the down-left arrows.

[2] See the first two steps of eqn. 7 in *Handout* xxi.

[3] As we'll discuss in later handouts, the iron-56 itself comes from earlier generations of stars which exploded as supernovae.

[4] Strictly speaking, bismuth-209 is radioactive, decaying by α emission; but its half-life is 2.01×10^{19} yr, over a billion times longer than the current age of the Universe. So, it's effectively stable.