Massive Stars through Helium Burning

Stars with masses $M \gtrsim 10\,M_\odot$ follow a quite different evolutionary path than the lower-mass stars we've been considering so far. On the main-sequence, their immense luminosities[1] mean that in spite of having more hydrogen fuel to burn, they consume this fuel at a greatly accelerated rate. Thus, a $10\,M_\odot$ star with a luminosity $\sim 6000\,\mathrm{L}_\odot$ has a main-sequence lifetime of only $\sim 20\,\mathrm{Myr}$, compared to the $\sim 10\,\mathrm{Gyr}$ of the Sun.

[1] Recall from *Handout* XX that main-sequence stars follow a steep mass-luminosity relation $L \sim M^{3.5}$.

However, the biggest evolutionary differences occur after exhaustion of hydrogen at the center. Then, massive stars move rapidly to the red in the Hertzsprung-Russell diagram, at approximately constant luminosity (see Fig. 1). During this *red supergiant* phase, their radii can exceed $10^3\,\mathrm{R}_\odot$ and their core temperature becomes hot enough ($\gtrsim 10^8\,\mathrm{K}$) to ignite helium fusion via the triple alpha process. This ignition occurs under non-degenerate conditions, and so — in contrast to stars like the Sun — no helium flash occurs.

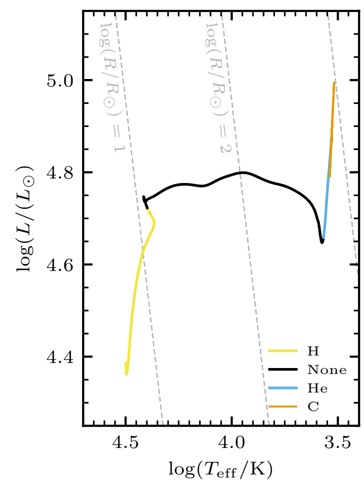

Figure 1: Evolutionary track in the Hertzsprung-Russell diagram for a *MESA* model of a $16\,\mathrm{M}_\odot$ star, spanning the main sequence through to core collapse. The track colors indicate the fuel being burned in the core; note that the burning stages beyond carbon are barely visible, because the star barely changes position in the diagram. Note also that the vertical scale spans less than an order of magnitude in luminosity; contrast this, e.g., with Fig. 1 of *Handout* XXII.

Massive Stars After Helium Burning

Hydrogen and helium burning are just the first stages in a cyclical process followed by all massive stars: upon the exhaustion of one nuclear fuel in the core, they contract and heat up to ignite the next fuel. In this cycle, carbon burning follows after helium burning at a core temperature $T_\mathrm{c} \sim 5 \times 10^8\,\mathrm{K}$, and proceeds primarily by the reaction

$$^{12}\mathrm{C}(^{12}\mathrm{C}, \alpha)^{20}\mathrm{Ne}. \tag{1}$$

The next stage, at $T_\mathrm{c} \sim 10^9\,\mathrm{K}$, is neon burning[2]:

$$^{20}\mathrm{Ne}(\gamma, \alpha)^{16}\mathrm{O}, \qquad ^{20}\mathrm{Ne}(\alpha, \gamma)^{24}\mathrm{Mg}. \tag{2}$$

[2] The first reaction here is an example of *photodisintegration*, and arises due to the abundance of energetic photons at the high burning temperatures.

This is followed, at $T_\mathrm{c} \sim 1.5 \times 10^9\,\mathrm{K}$, by oxygen burning[3]:

$$^{16}\mathrm{O}(^{16}\mathrm{O}, \alpha)^{28}\mathrm{Si} \tag{3}$$

[3] The reason why oxygen burning follows neon burning, even though oxygen has the smaller mass number, is that ^{16}O is a double-magic nucleus with 8 protons and 8 neutrons; therefore, it is unusually stable and difficult to burn.

Subsequent burning stages proceed by α-capture reactions, and steadily convert the silicon to heavier elements:

$$\begin{split} ^{28}\mathrm{Si}\,(\alpha,\gamma)\,^{32}\mathrm{S}\,(\alpha,\gamma)\,^{36}\mathrm{Ar}\,(\alpha,\gamma)\,^{40}\mathrm{Ca}\,(\alpha,\gamma) \\ ^{44}\mathrm{Ti}\,(\alpha,\gamma)\,^{48}\mathrm{Cr}\,(\alpha,\gamma)\,^{52}\mathrm{Cr}\,(\alpha,\gamma)\,^{56}\mathrm{Ni} \end{split} \tag{4}$$

The α particles required by these reactions are produced by photodisintegration of other ^{28}Si nuclei. Although this sequence suggests that ^{56}Ni is the final product, in fact neutron captures[4] along the way mean that the core ends up composed predominantly of ^{56}Fe. This

[4] Like the α particles, the neutrons come from photodisintegration of other nuclei.

is the most stably bound of all isotopes, and no further nuclear energy can be extracted: the burning cycle has come to an end. As we shall see, an iron core inevitably collapses soon after its formation, triggering a supernova explosion.

Fig. 2 illustrates the progression of core burning from hydrogen through to iron for a $16\,M_\odot$ star, plotting the central abundances of various isotopes as a function of time remaining until core collapse. Note how each burning phase is shorter than the previous one; thus, while core oxygen burning takes around a year, silicon burning lasts only a few days. As the star exhausts a given fuel in the core, that fuel continues to burn in a shell around the core; therefore, the composition profile of the star at the instant of collapse resembles an onion, with nested shells of hydrogen, helium, carbon, neon, oxygen and silicon (going from surface inward) lying atop the iron core.

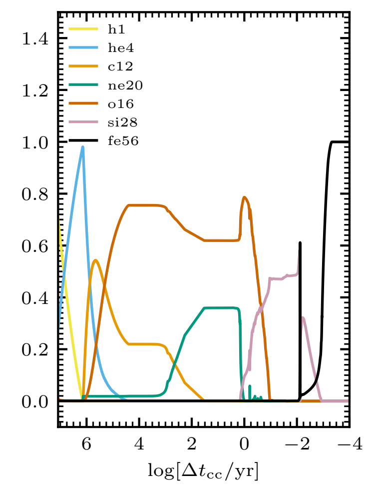

Figure 2: Central abundances of various isotopes during the evolution of the 16 $M_\odot$ *MESA* model (Fig. 1), plotted as a function of time until core collapse Δt_{cc}. The sharp spike in the ^{56}Fe abundance is a numerical artifact.

The Eddington Limit

Throughout their evolution, both on the main-sequence and after, massive stars experience strong stellar winds driven by radiation pressure acting on material in the stars' atmospheres[5]. To understand the origin of these winds, let's write down the equation of hydrostatic equilibrium with separate terms on the left-hand side involving the gas pressure $P_{\rm gas} \equiv P_{\rm ion} + P_{\rm el}$ and radiation pressure $P_{\rm rad}$:

$$\frac{\mathrm{d}P_{\rm gas}}{\mathrm{d}r} + \frac{\mathrm{d}P_{\rm rad}}{\mathrm{d}r} = g\rho \qquad (5)$$

Applying this to the surface layers of a star, where energy is transported by radiation, we can write[6]

$$\left.\frac{\mathrm{d}P_{\rm gas}}{\mathrm{d}r}\right|_{r=R} = g\rho\left[1 - \Gamma_{\rm edd}\right], \qquad (6)$$

where we introduce the *Eddington parameter* as

$$\Gamma_{\rm edd} = \frac{\kappa L}{4\pi G M c}. \qquad (7)$$

Recalling that g must be negative, we see that $\Gamma_{\rm edd} > 1$ corresponds to a positive gas pressure gradient at the stellar surface. This is inconsistent with the boundary condition that $P_{\rm gas}$ become small; hence, stars with $\Gamma_{\rm edd} > 1$ — mostly, massive stars due to their immense luminosities — cannot remain in hydrostatic equilibrium at their surface, and instead launch radiation-driven winds.

[5] Contrast this with low-mass stars, which harbor strong winds only near the tips of the RGB and AGB.

[6] To derive this result, set $P_{\rm rad} = aT^4/3$ and apply the radiative diffusion equation (eqn.6 of *Handout* XII) to evaluate the temperature gradient.

Further Reading

Kippenhahn, Weigert & Weiss, §§35.1,32.3; *Ostlie & Carroll*, §15.1; *Prialnik*, §9.9.