7.4 Evolution on the Main-Sequence

Main-sequence (m-s) stars evolve on the nuclear time-scale which is very slow in contrast to the Kelvin-Helmholtz time-scale which governs the length of the pre-main-sequence phase. For the Sun, the contraction time to the m-s $\tau_{K-H} \sim 30 \times 10^6$ yr and $\tau_{m-s} \sim 10^{10}$ yr. For a $9\,\mathrm{M}_\odot$ star, the corresponding times are much shorter with $\tau_{K-H} \sim 10^5$ yr and $\tau_{m-s} \sim 20 \times 10^6$ yr.

As shown in Sect. 7.3, the m-s can be split into two parts depending on the energy generation process for H-burning:

- *(a) Lower Main Sequence (LMS) Stars:* have $M < 2\ \mathrm{M}_\odot$, $T_c \leq 2 \times 10^7$ K and $T_{\text{eff}} \leq 10^4$ K, corresponding to spectral types F and later. Energy generation is via the p-p chain with the energy generation rate $\epsilon \propto T^n$ and $n = 3.6$–6 (depending on T_c). They have radiative cores since the temperature sensitivity is comparatively low.

  LMS stars have convective envelopes because of their high opacities. The extent depends on mass: at $1\,\mathrm{M}_\odot$, the convective envelope accounts for 3% by mass whereas at $0.5\,\mathrm{M}_\odot$, the convective envelope increases to 40% by mass.

  Note: stars with $M \leq 0.25\,\mathrm{M}_\odot$ are fully convective.

- *(b) Upper Main Sequence (UMS) Stars:* have $M \geq 2\ \mathrm{M}_\odot$, $T_c \geq 2 \times 10^7$ K and $T_{\text{eff}} \geq 10^4$ K, corresponding to spectral types A and earlier. Energy generation is via the CNO cycle with $n = 13$–20. This high temperature sensitivity and resulting high $L/(4\pi r^2)$ means that the cores will be convective. The envelopes of UMS stars are radiative because of their high temperatures.

  The mass of the convective core M_{CC} increases with the total mass because of the large increase in ϵ with temperature. In a $3\,\mathrm{M}_\odot$ star, $M_{CC} = 0.17\,\mathrm{M}_{\mathrm{TOT}}$ and in a $15\,\mathrm{M}_\odot$ star, $M_{CC} = 0.38\,\mathrm{M}_{\mathrm{TOT}}$.

Evolution on the m-s is driven by the gradual conversion of H to He. This increases μ and to maintain the pressure, the density has to increase through core contraction which in turn causes the temperature to increase. As a result, ϵ increases and this causes an increase in L. This effect follows from eqn. (7.19, 7.20) relating T and L to μ. For the Sun, L has increased by 30% from ZAMS to the present.

While the central parts of the star contract, the outer parts expand – the opposite behaviour of the core and envelope is a characteristic feature of stellar evolution. This is discussed in more detail below.

The precise details of the evolution on the m-s, and in particular how it ends, depend strongly on the mass of the star. For LMS stars with radiative cores, there is no mixing and the abundance of H decreases most rapidly at the centre. Energy production still continues in a "thick shell" around the centre. Consequently there is a gradual transition to the next evolutionary phase with fusion in a shell around a core consisting of He and heavier elements.

In contrast, UMS stars have fully mixed cores because of convection and hence the H abundance decreases uniformly throughout the core. H is then essentially exhausted simultaneously throughout the central energy-producing region. In the final stages of H fusion, the star contracts in an attempt to maintain the energy production by increasing T_c. This produces a "left hook" in the HRD. The time spent in this phase is very short compared to the m-s phase. Hence very few stars are found in this final phase of m-s evolution. As H is exhausted, the star establishes a H-burning shell source around the core.

The m-s lifetime $\tau_{m-s} \propto L/M$ and since $L \propto M^3$, then $\tau_{m-s} \propto M^2$. Massive stars have m-s lifetimes of a few million years compared to $10^{10}\,\mathrm{yr}$ for the Sun. The lifetime of a massive star ($M > 15\,\mathrm{M}_\odot$) on the m-s is, however, increased because of mass loss. For example, a 25 $\mathrm{M}_\odot$ star has $\tau_{m-s} = 6 \times 10^6$ yr and a mass loss rate of $\sim 10^{-6}$ $\mathrm{M}_\odot$ yr^{-1}. Over its m-s lifetime, it will have lost 6 $\mathrm{M}_\odot$ and thus τ_{m-s} will increase since the star will end its m-s phase with a mass of $21\,\mathrm{M}_\odot$. Low mass stars like the Sun lose a negligible amount of mass on the m-s.

7.5 Evolution off the Main-Sequence to the Red Giant Branch

At the end of central hydrogen fusion, the star has a helium core surrounded by a *shell source* where H fusion continues. The helium core grows as a result of "ash" from the H-burning shell and contracts under gravity. When the core contracts, the envelope expands. This is known as the "mirror principle" or "shell-burning law": the contraction (or expansion) reverses at the shell source. No simple explanation has been given for this phenomenon because the physics is very complicated. In simple terms, if we assume the virial theorem to hold, and that the total stellar energy remains constant, then the gravitational and thermal energy are each conserved. The contraction of the core must be accompanied by the expansion of the envelope to conserve the gravitational potential energy. At the same time, the heating of the core must result in a cooling of the envelope for the thermal energy to be conserved. If the total energy does not remain constant but $L_{\mathrm{nuc}} > L$, the envelope will expand considerably on core contraction. Only detailed computations can determine the effect on the envelope of departures from thermal equilibrium. All numerical computations of the evolutionary phase following H exhaustion in the core obtain envelope expansion on core contraction as solutions of the stellar evolution equations.

When the envelope expands, the effective temperature decreases, and the star moves towards the red giant branch. When the star reaches the Hayashi track, a further decrease in T_{eff} is impossible since the star would move into the "forbidden" region of the HRD. The continuing expansion therefore takes the star up the red giant branch. The luminosity increases as the core continues to contract and the temperature in the shell source increases. The need to transfer an increasing energy flux and the increasing opacity of the cool envelope causes the envelope to become convectively unstable. The ascent of the red giant branch continues until helium fusion can take place.

The transition from a m-s to a RG configuration is of short duration – typically 1–2% of the m-s lifetime. Hence very few stars are observed in this phase, leading to a conspicuous gap in the observed HRD between the m-s and RG phases. This gap is called the *Hertzsprung gap.*

The subsequent evolution depends sensitively on the stellar mass.