Stellar Evolution of Single Stars

Stellar evolution can be divided into 3 distinct phases:

1) **Pre-main sequence evolution**: a relatively short (~ $10^{7-8}$ yrs) phase, but involving many complex processes. An active research area.

2) **Main sequence phase**: the longest phase of a star’s life ~ $10^{10}$ yrs for the Sun. Have M-L-R relations, Russell-Vogt theorem, as previously discussed.

3) **Post-main sequence evolution**: will discuss in detail next.

**Tools:**

The most important tool for this discussion is the theoretical HR diagram of L vs. $T_e$ and its observational counterpart the $M_V$ vs. B-V diagram.

A variety of other graphs and schematics are also useful. We will discuss stellar evolution mostly descriptively, because it is a complex, numerically-based theory, with few simple, analytic results. We begin with the life story of the (future) Sun.
Low-Mass Stellar Evolution

Stages in the post-M. S. life of a Sun-like star.

1) Core hydrogen exhaustion.

H becomes scarce in the core $\rightarrow$ decreased energy production $\rightarrow$

Unbalanced gravity $\rightarrow$ contraction

Then the core begins a nearly adiabatic Kelvin-Helmholtz contraction. $\rho_c$, $T_c$, and $L$ increase.

When $\rho$, $T$ outside the core become large enough $\rightarrow$ H-burning in a shell.
2) **Subgiant Phase**

For stars with $M \geq M_{\text{sun}}$, H is burnt in a **thick shell** between points 4-7 in Iben’s graph. At points 7-11 the shell narrows. The core continues to **contract**, as more He is added.

![Diagram of subgiant phase](image)

In this phase $L \approx$ constant, but energy generation increases in the shell. Then pressure on the envelope increases $\Rightarrow$ envelope expands as work is done on it.
At the surface, $L \sim R^2 T^4$, $L \approx$ constant, so increasing $R \rightarrow T$ decreases.

The star becomes a subgiant.

Once the star reaches the “Hayashi line”, the opacity increases, and no further $T$ decrease is possible.

3) **The Red Giant Phase**

As time goes on the envelope becomes progressively more convective. The star “ascends the Hayashi line” to become a red giant.

In this stage $T \approx$ constant, so $L \sim R^2$, and $R$ increases greatly.
4) He Flash & Evolution to the Horizontal Branch.

Eventually, $P_c$ becomes high enough for He burning. In a 1 $M_{\text{sun}}$ star this occurs with a thermal instability ——> **He flash.**

The cycle of instability increases until the degeneracy is “lifted”.

I.e., $nkT \approx P_{\text{degen}}$. 
Then the core expands. This weakens the H shell burning and $L$ decreases. The giant envelope shrinks. The star descends to the horizontal branch (HB).

The HB is like a He main sequence, but it's not exactly that due to the extra luminosity from the H burning shell.

How much mass is lost up to this point?? From now on, the calculations get more uncertain due to this and other factors.

The position of a star on the HB depends on the composition ("branch vs. clump")
5) Post-HB Evolution

...is qualitatively similar to post-main sequence evolution.

He exhaustion $\rightarrow$ contraction, \( \rho_c, T_c \) increase $\rightarrow$ He shell burning.

L increases $\rightarrow$ formation of a red giant envelope again.

The star ascends the giant branch a second time. The second ascent is higher than the first.
6) Asymptotic Giant Branch ("second ascent giant")

Many complications to the theory arise on the AGB, including:
- thermal relaxation oscillations or pulses.
- much mass loss
- big pulsations

We will consider these shortly.
Overview of post-main sequence evolution for various masses.

Fig. 2. Paths in the Hertzsprung-Russell diagram for metal-rich stars of mass (M/M\(_\odot\)) = 15, 9, 5, 3, 2.25, 1.5, 1.25, and 1. L and T, as in Fig. 1. Traversal times (in years) between labeled points are given in Table 1.