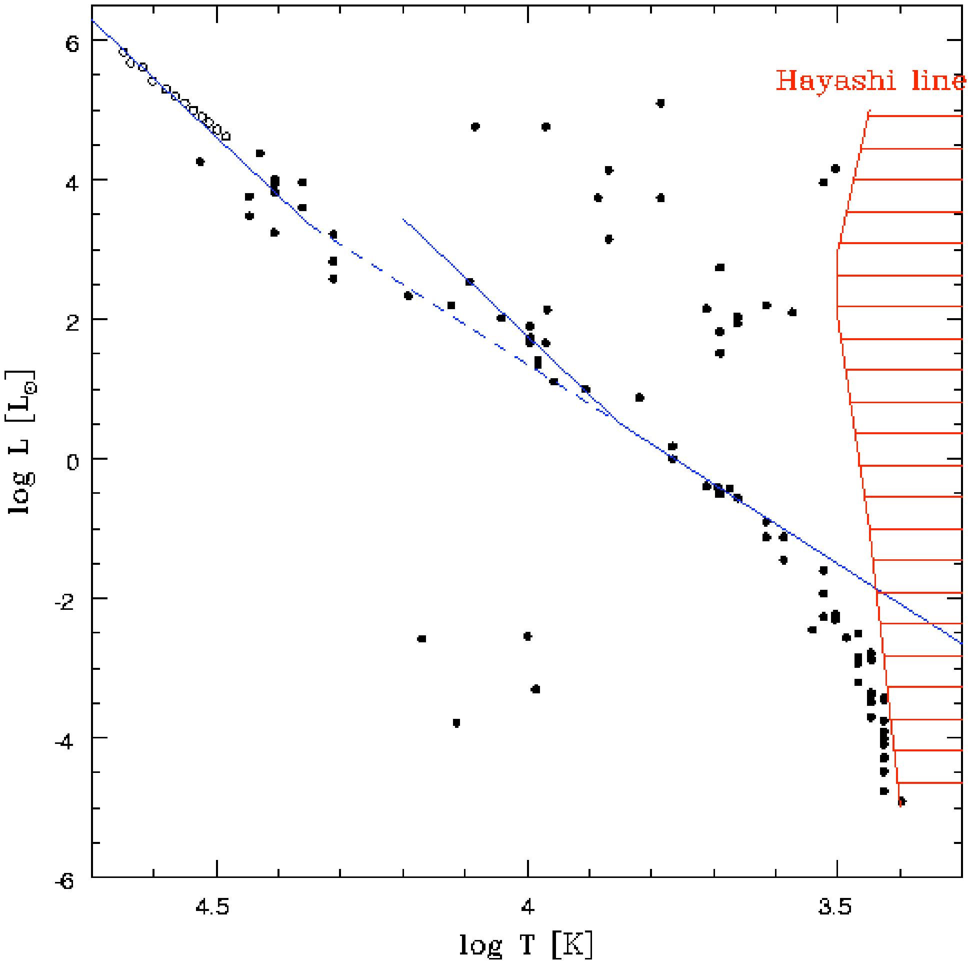
# 9. Early Stellar Evolution

## 9.1 Hayashi Line

For a fully convective star,

$$\log L \approx 20 \log T_{eff} - 4 \log M + const \quad (204)$$



Hashed area delineates a “forbidden” (unstable) region.

## 9.2 Pre-main-sequence Evolution

During star formation, gravitational collapse of a gas cloud forms a proto-star. (original cloud → lots of smaller clouds → lots of small(ish) stars). Released gravitational energy used to

- Dissociate $H_2$: $\chi_{H_2}$
- Ionize $H$ and $He$

Assume collapse from $\infty$ to the proto-star radius $R_{ps}$.

$$\alpha \frac{GM^2}{R_{ps}} \approx \frac{M}{m_H}\left(\frac{X}{2}\chi_{H_2} + X\chi_H + \frac{Y}{4}\chi_{He}\right) \quad (205)$$

For $Y \approx 1 - X$ and $\alpha \approx 0.5$, Z’s ignored – assuming only hydrogen and helium.

$$\frac{R_{ps}}{R_{sun}} \approx \frac{50}{1-0.2X}\frac{M}{M_{sun}} \quad (206)$$

Average temperature from the virial theorem (assuming all internal energy is thermal energy, and that the temperature is the same throughout),

$$T = \frac{\alpha}{3}\frac{m}{k}\frac{GMm_H}{R_{ps}} \approx 6 \times 10^4 k \quad (207)$$

The proto-star is fully convective. The star is not yet hot enough for fusion.

During the continuing collapse,

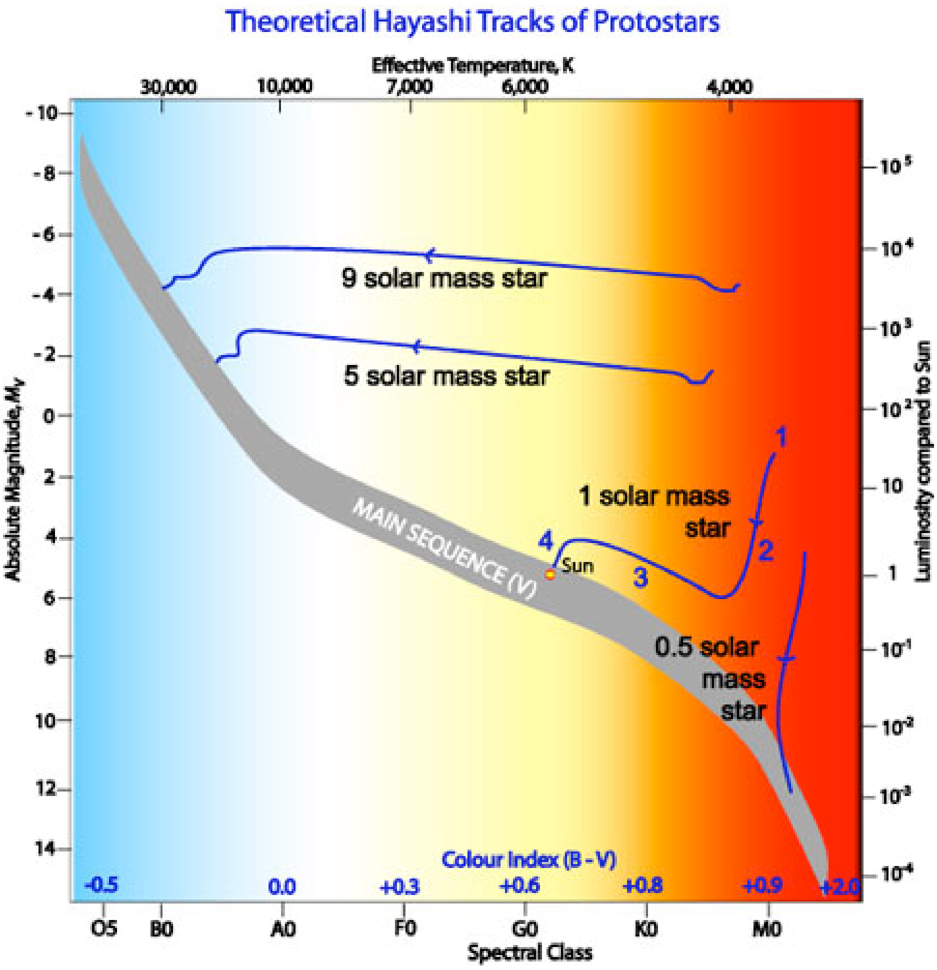
- Radius decreases
- Luminosity decreases roughly as $R^2$
- $T_{eff}$ nearly constant
- $T_c$ increases

We won't be able to see the star much at this point, as the luminosity drop so much.
→ missing point in stellar evolution.
The star evolves on a steep Hayashi track.

Next phases:

- Once fully ionized, opacity drops
- Core no longer convective: star leaves Hayashi track. Convection stops from inside out.
- $T_{eff}$ increases and $L$ increases.

Finally gradual ignition of various chains of hydrogen burning (first burning deuterium, then hydrogen, …). Star has now arrived at the Main Sequence.



The dip is where nuclear fusion begins. At all times, the star will head towards higher temperatures. The dips in the high mass stars are caused by the CNO cycle starting.

### 9.3 Main Sequence

$M \leq 2M_{sun}$

p-p cycle:

For $4\times10^6 K \leq T_c \leq 2.4\times10^7 k$, $\varepsilon \propto T^n$, $6 \geq n \geq 3.5$. Typically around 4.

Cores radiative, cool envelopes – H ionization zones – outer convection zones.

$M > 3M_{sun}$

CNO cycle:

For $1.2\times10^7 K \leq T_c \leq 5\times10^7 k$, $\varepsilon \propto T^n$, $20 \geq n \geq 13$ Typically 15 or 16.

Energy generation centrally condensed – steep gradients → convective core.

Hot envelopes which are radiative.

In between these masses, there is a mixture of both cycles.

### 9.4 Core Evolution

Initially core is chemically homogenous. The energy generation rate is

$$\varepsilon = \varepsilon_0 \rho T^n \quad (208)$$

$$\varepsilon_0 \propto n_j n_k \quad (209)$$

Low mass stars: pp-cycle

For the pp cycle, $n$ is the hydrogen number density.

$$n_j = n_k = n_H \propto X \quad (21)$$

Therefore,

$$\varepsilon \propto X^2 \rho T^n \quad (211)$$

Fusion causes $X$ to slowly decrease in the core. Hence the star will slowly turn off. Why doesn't this happen? Hydrostatic equilibrium.

As the pp-cycle burns hydrogen to helium,

- X decreases
- So $\varepsilon$ decreases
- Hydrostatic equilibrium is lost
- So the core contracts
- Temperature and density rise
- $\varepsilon$ increases: equilibrium renewed
- But at higher luminosity.

On the main sequence, stars slowly increase in luminosity.

For the sun,

$X$ has reduced by half within about $0.3R_*$; luminosity has increased by half since birth.

Finally hydrogen is fully depleted at the centre of the star, and fusion ceases there. The star now contains;

- Inert, isothermal $He$ core
  e.g. $r \le 0.03 R_*$
- Thick H-burning shell
  $0.03 \le r \le 0.3 R_*$

The He-core increases in mass and radius.

Higher mass stars: CNO cycle

Their evolution differs in two ways from the lower mass stars:

1. The CNO cycle has an energy generation rate.
   $\varepsilon \propto X Z_{CNO} \rho T^n$
   where $Z_{CNO}$ is the mass fraction of CNO.
   The energy generation rate is less sensitive to the hydrogen fraction:
   - The cores do not contract as much when $H$ becomes depleted
   - The luminosity increases because of steep temperature dependence $n$.
2. CNO-cycle stars have convective cores.
   A convective region has a uniform composition, due to mixing.
   Note: uniform composition does not mean uniform nuclear burning rate.
   Therefore, H is depleted uniformly over the whole convective region.
   - No central, inert He core
   - Higher mass stars do not have a thick-shell burning stage

### 9.5 Main sequence life times

$$L \propto M^3$$

$$t_{MS} \propto \frac{M}{L} \propto M^{-2} \quad (213)$$

Longer lifetimes are possible if:

1. Convective cores increase available hydrogen (lowest mass and high mass stars)
2. Mass loss through stellar winds decrease mass (high mass stars)

Table of stellar life times on the main sequence:

| $M\left[M_\odot\right]$ | $t_{MS}$ [years] |
|---|---|
| 0.1 | $6\times10^{12}$ |
| 0.5 | $7\times10^{10}$ |
| 1.0 | $1\times10^{10}$ |
| 1.5 | $2\times10^{9}$ |
| 5 | $7\times10^{7}$ |
| 15 | $1\times10^{7}$ |
| 25 | $6\times10^{6}$ |