7.2 The Pre-Main Sequence Phase

The initial collapse of a proto-star proceeds on the dynamical time-scale, $\tau_{\rm dyn} \sim 1/(G\rho)^{1/2}$. Here ρ is low $\sim 10^{-10}\ \mathrm{kg\,m^{-3}}$ so time-scale is quite slow. The internal temperature rises according to Virial Equilibrium and the molecules (mainly H_2) dissociate. Hydrogen and eventually He atoms are ionized. There is now sufficient pressure to oppose gravity and hydrostatic equilibrium is established. The gaseous condensation has now become a proto-star.

We can roughly estimate the characteristics of a proto-star by assuming that all the gravitational P.E. Ω released in collapse to the proto-stellar radius R_{ps} from infinity was absorbed in the the dissociation of molecular hydrogen and the ionization of H and He:

$$\frac{1}{2}\frac{GM^2}{R_{ps}} \approx \frac{M}{m_H}\left(\frac{X}{2}\chi(H_2) + X\chi(H) + \frac{Y}{4}\chi(He)\right)$$

where $\chi(H_2) = 4.5$ eV, $\chi(H) = 13.6$ eV, $\chi(He) = 24.6 + 54.4$ eV, and taking $Y = 1 - X$, we obtain:

$$\frac{R_{ps}}{R_\odot} \approx \frac{43(M/M_\odot)}{1 - 0.2X}. \qquad [7.12]$$

This represents the maximum radius for a stable star as it begins its evolution. The average internal temperature can be estimated from the Virial theorem:

$$\bar{T} \approx \frac{\mu m_H}{3k}\frac{GM}{R_{ps}} \approx 10^5\ \mathrm{K} \qquad [7.13]$$

This temperature extrapolated to the core is far too low for thermonuclear reactions to start. At this temperature, the opacity due to H^- is high and the luminosity is also high (large radius). The combination of high L and κ means that the star is fully convective except for a thin radiative envelope.

The initial stellar model can therefore be well approximated by a polytrope with $\gamma = 5/3$ or $n = 1.5$ and a radius given by [7.12]. Hayashi first computed pre-main-sequence evolutionary tracks for fully convective stars in the early 1960's – the resulting tracks are called Hayashi tracks.

Solving the mass-radius relation for a polytrope (eqn. 6.33) together with the equations of hydrostatic equilibrium and the Stefan-Boltzmann law, it can be shown that:

$$\log T_{\rm eff} = 0.14 \log M + 0.01 \log L \qquad [7.14]$$

The temperature is nearly independent of L and is only weakly dependent on M. This means that fully convective stars all fall in the same cool part of the HRD with $T_{\rm eff} \approx 3000$–$5000\,$K, and the tracks are almost vertical.

For a given mass and chemical composition, no fully convective star can lie to the right of its given Hayashi track because convection is the most efficient means of energy transport and the star will radiate like a black body. This gives rise to the *Hayashi line* and the *Hayashi forbidden zone* to the right where stable stars cannot exist.

Proto-stars evolve at near constant $T_{\rm eff}$ and L decreases ($\propto 1/R^2$) as star continues to contract. The star will therefore descend along its Hayashi track.

In time, as the internal temperature continues to rise, ionization is completed and the opacity drops. The stellar luminosity L is now less than the energy that can be transported by radiation $L_{\rm rad}$ and the core becomes radiative. The star moves away from its Hayashi track towards higher $T_{\rm eff}$ and follows a "Henyey" track which is $\sim$ horizontal.

The increasing core temperature causes nuclear reactions to start and for the first time, the luminosity starts to rise. Star finally arrives on the zero age main sequence (ZAMS) when H is fully ignited in the core.

The relevant time-scale during the pre-main-sequence phase is τ_{KH}. Stars in this phase are hard to detect because the time-scale is short and they are shrouded in their natal molecular clouds. Low mass proto-stars are highly variable (convective) and are called T Tauri stars.

More massive stars ($M \geq 5$ M$_\odot$) become stable against convection very quickly and spend a very short time on their Hayashi tracks. Most of their pre-ms evolution is on the Henyey track as fully radiative stars. Stars with $M \approx 0.5$ M$_\odot$ do not become stable against convection and they evolve vertically onto the ZAMS as fully convective stars.