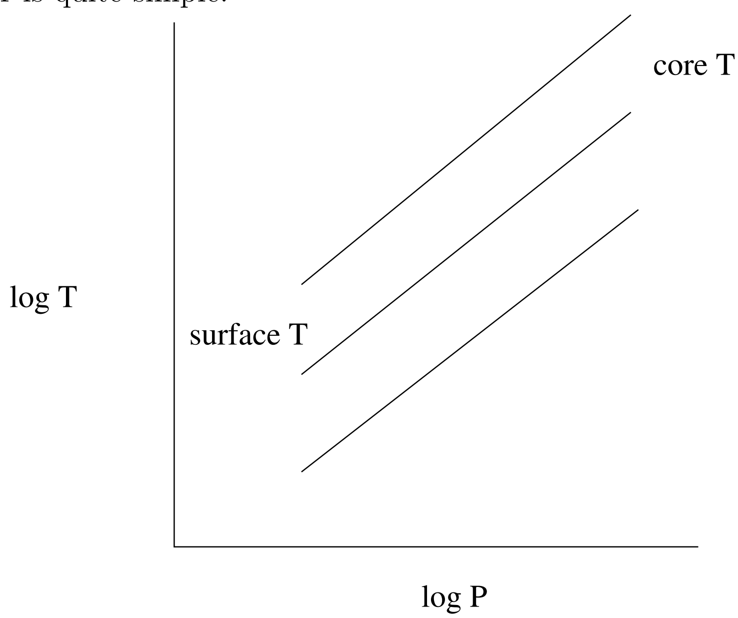
18 Astro notes 2017/02/24 - Fri - Star Formation - Hayashi; interstellar dust

18.1 Hayashi contraction phase

As stated last time, we want to find structure of star which is fully convective from surface to interior, in which structure is set by conditions at the photosphere. Hayashi's insight was that the surface boundary condition controls the evolution of these protostellar objects.

For protostellar objects, the inside of the star is fully convective. This means that material is constantly moving from surface to interior, and is therefore well-mixed and at nearly constant entropy. So the T profile can be approximated as an adiabatic profile. For adiabatic compression $T \propto P^{2/5}$. This means the pressure-temperature structure of the star is quite simple:



At the photosphere, where $T \simeq T_{\rm eff}$, we have

$$P_{ph} = \frac{g}{\kappa}$$

Where κ is the "opacity" and sets how "hard" it is for photons to carry energy through the medium. Note that these are not free-streaming photons, but thermally diffused ones. The flux transmitted follows

$$F = \frac{1}{3}\frac{c}{\kappa\rho}\frac{d(aT^4)}{dz}$$

where z is some spatial coordinate (we will use radius in a moment). Higher κ means a higher T and higher T gradient is needed to transfer energy at a given rate.

By setting the surface T and P the surface condition sets the power-law relation that the interior of the star follows. It selects among the straight lines in this plot. This determines the central values, T_c and P_c. Thus we know

$$\frac{T_c}{P_c^{2/5}} \sim \frac{T_{ph}}{P_{ph}^{2/5}} = \frac{T_{eff}\kappa^{2/5}}{g^{2/5}}$$

The relation $T \propto P^{2/5}$, the ideal gas law, and the equation of hydrostatic balance allows us to solve for the gross structure of the star. This is gives the following relations for fully convective star:

$$P_c = 0.77\frac{GM^2}{R^4}$$

and

$$T_c = 0.54\frac{GM\mu m_p}{k_B R}$$

this gives that

$$k_B T_{eff} = 0.6\frac{GM\mu m_p}{R}\left[\frac{R^2}{M\kappa_{ph}}\right]^{2/5}$$

So now we NEED to understand the opacity, κ, at the photosphere.

Putting in Thomson scattering – which is the opacity from free electrons also called "electron scattering" opacit – gives a solution that is so cold that electrons can't be free, inconsistent. What Hayashi did is find that the main opacity is from H^-. The last electron is very weakly bound, about 0.75 eV. We'll find that the temperatures are 2000-3000 K. Electrons come from reactive(or low valence energy) elements Na, Li, etc. This process is very temperature sensative, at lower temp, metals not ionized, at higher there is no H^-.

The opacity is from the photo-ionization of H^-, $\gamma + H^- \rightarrow H + e^-$. Figuring out the opacity is hard. The fitting form is

$$\kappa_H = 2.5 \times 10^{-31}\rho^{1/2}T^9 \text{ cm}^2/\text{gr}$$

put this into the above and you get

$$T_{eff} \simeq 2500 \text{ K}\left(\frac{M}{M_\odot}\right)^{1/7}\left(\frac{R}{R_\odot}\right)^{1/49}$$

Almost independent of the radius, so the lines are vertical. Also the increase in effective temperature with mass. You will show in the homework that this relation allows the star to have a wide range of luminosities with nearly the same T_{eff}.

Pre Main sequence stars with calculated tracks. Also see MESA paper (http://adsabs.harvard.edu/abs/2011ApJS..192....3P) figure 23 as an example. See that Hayashi track for protostar is similar to track for giants. Similar physics determine the outer boundary.

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PASP
100, 1479
(1988)

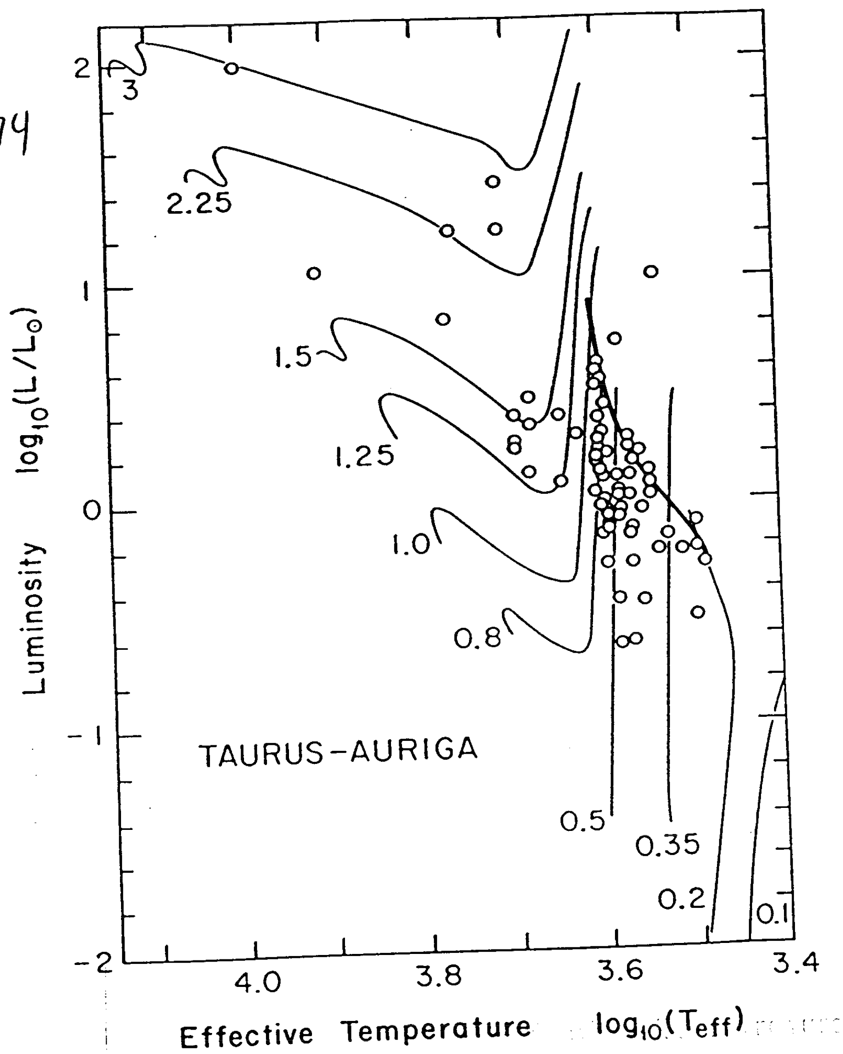

FIG. 4—Observational H-R diagram of the Taurus-Auriga molecular cloud complex. Open circles represent the T Tauri observations of Cot Kuhi (1979). The light solid lines are the theoretical pre-main-sequence tracks of Iben (1965) and Grossman and Graboske (1971), with the appr masses (in solar units) labeled. The heavy solid line is the birthline of Stahler (1983).

+ Iben ApJ, 141, 993

+ Stahler ApJ, 274, 822
332, 804

18.2 Dust extinction

observed magnitudes are effected by extinction

$$m_\lambda = M_\lambda + 5\log_{10} d - 5 + A_\lambda$$

where d is the distance in parsecs and $A_\lambda > 0$ is called the extinction. The amount of extinction depends on wavelength, even for the same amount of dust. The amount of dust is typically measured using optical depth. For some intensity field (parallel flux rays) I_λ,

$$\frac{I_\lambda}{I_{\lambda,0}} = e^{-\tau_\lambda}$$

where τ_λ is called the optical depth. Working this out gives

$$m_\lambda - m_{\lambda,0} = -2.5\log_{10}(e^{-\tau_\lambda}) = 2.5\tau_\lambda \log_{10} e = 1.086\tau_\lambda$$

or

$$A_\lambda = 1.086\tau_\lambda$$

Next time we will discuss optical depth and the wavelength dependence.