PHY 474/374 Spring 2021

Class Summary—Week 6, Day 1—Monday, May 3

Evolution before the Main Sequence

Stars form in sub-parsec scale clumps of gas deep inside Giant Molecular Clouds (GMCs) when the gravitational force overwhelms any other forces opposing the collapse of material. GMCs are huge structures, about 20-200 pc in size (diameter), containing $10^4 - 10^6\ M_\odot$ of molecular and atomic gas, roughly in equal proportion. Note that there is confusing use of terms in the literature, but most authors have tried for uniformity in recent years; isolated star formation takes place in cores, and clustered star formation in clumps.

As gravitational potential energy is converted to kinetic energy in these collapsing clumps (or cores), the deep interior of the clump (or core) heats up; recall that the kinetic definition of temperature of a gas is that it is the average kinetic energy of the gas molecules. At the center of the clump (or core), a protostar develops, and begins to amass material (usually by infall of material from a disk that has formed around the protostar). Eventually, infall will stop. The protostar continues to decrease in radius and increase the temperature in its core well past the end of the infall stage. Eventually, once the temperature has reached about 10 million K in the core of the star, nuclear fusion begins and the star settles down onto the Main Sequence shortly thereafter.

This simple description above hides many complexities, of course. We won't go into them here, since we teach a whole course on the subject of Star Formation. For additional detail regarding some of the challenges of learning about star formation, please read **Section 10.1** (*Dalsgaard*, **pages 129-130**).

Comments on the Initial Stages

Star formation begins when the sub-parsec scale clump (or cloud core) becomes unstable to gravitational collapse. Infall of material into the central region of the clump (or cloud core) which develops into a protostar is usually accompanied by the formation of a disk around the protostar, and bipolar outflows. Several stages have been identified in observations and labeled as Class 0, I, II, and III respectively. The Class II phase is also known as the **T-Tauri** phase.

At some point during the T-Tauri stage, infall stops, and we can see the central object at optical wavelengths and place it in an HR diagram. The **HR (Hertzsprung-Russell) diagram** is essentially a plot of luminosity *vs.* temperature, but it takes some getting used to, since T is plotted backwards, increasing from right to left. *On Question 1 of today's worksheet*, you answered some questions on the location of objects in the HR-diagram in order to get oriented to it.

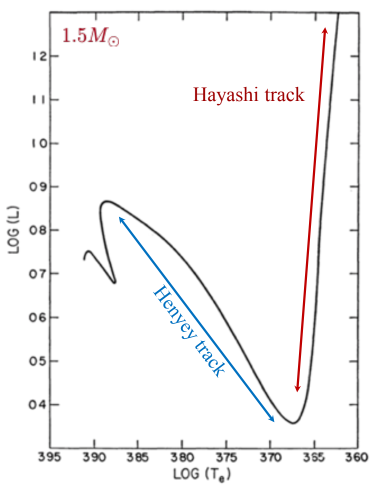
Once infall stops, the star has attained its final mass, though not yet its final radius. We usually label such stars as **pre-main sequence stars** (although, as usual, there is confusing usage of the term in the literature). Since it is no longer getting energy from accretion, its source of energy is just the potential energy released by its gravitational contraction.

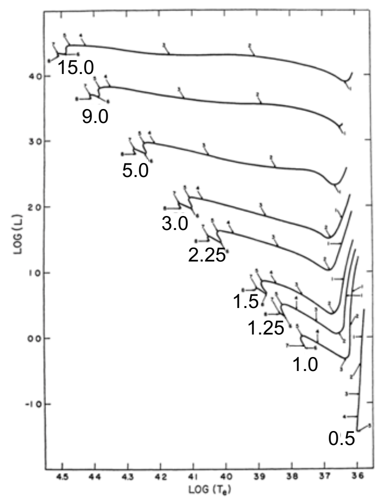
At this stage, a pre-main sequence star is fully convective. Since the luminosity of a star, $L \sim R^2 T^4$, and the star is still quite large, it will be bright. We will now learn about the subsequent evolution of a pre-main sequence star, until it begins nuclear fusion to get on to the Main Sequence.

The Hayashi Track

When we start working with pre-main sequence stars (that is, about the time it appears on an HR diagram), it is fully convective. In the language that we learned in previous weeks, the temperature gradient in the star is super-adiabatic; that is, the temperature gradient is steeper than the adiabatic gradient, which is the condition that leads to convection in the first place.

Let's follow the evolution of this star on the HR diagram. The plots below are taken from Iben (1965), posted in the optional reading for this class.





The plot on the right shows the tracks on the HR diagram for stars of different masses like $0.5\ M_\odot, 1.0\ M_\odot$, and so on, whereas the plot on the left shows the track of a $1.5\ M_\odot$ star by itself. Luminosity is in units of $L_\odot = 3.86 \times 10^{33}$ erg/sec and surface temperature T_e in units of K. Note that numbers on both axes have a decimal point after the first number, that is, $\log(T_e)$ values are 3.95, 3.90, and so on from left to right, whereas L values are 0.4, 0.5, and so on from bottom to top.

Let's focus on the plot in the left panel for a $1.5\ M_\odot$ star.

- When the star appears in the HR diagram (top right), it is still largely convective, and the stage marked in dark red is known as the **Hayashi track**.
- Note that when it appears on the HR diagram at the top right, the star has attained its final mass (infall has stopped), but not its final radius (it is still contracting).
- For this stage, we see that the surface temperature T_e (also known as the effective temperature, hence the subscript) remains roughly constant, even as the luminosity drops. Recall that $L \sim R^2 T_e^4$, so this makes sense. The temperature is roughly constant, and the star is contracting, so the decrease in R leads to a decrease in L.
- If the star is contracting, however, the central temperature in the core of the star must be increasing, which means the opacity in the interior is dropping. This leads to a flattening of the radiative temperature gradient in the interior of the star.
- Eventually, the radiative temperature gradient becomes less steep than the adiabatic temperature gradient in a finite region near the center of the star, leading to the development of a radiative core, which continues to grow.

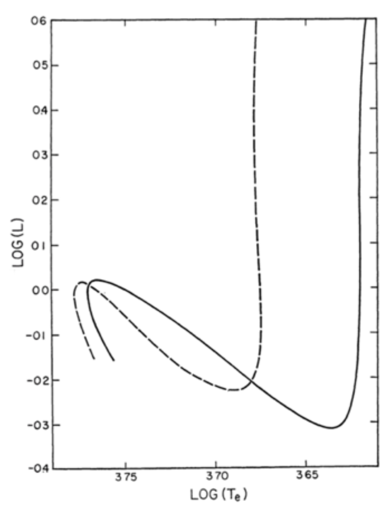
The Henyey Track

Once a star's core becomes radiative (generally for stars with $M > 0.8\ M_\odot$), the star makes a sharp turn to the left on the HR diagram, and goes on to the **Henyey track**.

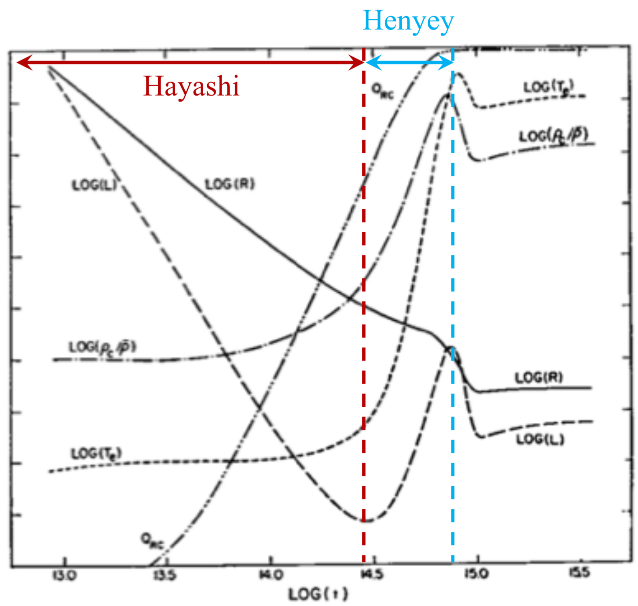
- This is because the core is sufficiently hot for the opacity to drop, making convection less efficient, and the core fully radiative.
- The T_e resulting from radiative transport is evidently higher than the T_e that convection could produce, and continues to rise as the interior temperature rises with contraction.
- The star has reached a new equilibrium. The rising surface temperature should cause an increase in luminosity, as long as it is not canceled by shrinking radius. Depending on its mass, luminosity remains constant or increases slightly (for intermediate mass stars) and the surface temperature increases slightly (or substantially for massive stars), as it continues to contract slowly.
- Stars with $M < 0.8\ M_\odot$ never develop a radiative core and reach the Main Sequence immediately after the Hayashi track.
- Higher mass stars spend very little time on the Hayashi track before developing a radiative core and moving nearly horizontally across the HR diagram on the Henyey track.

At the end of its time on the Henyey track, the star commences nuclear fusion in its core. It hasn't reached equilibrium yet, however, so the star continues to contract, moving down in luminosity toward its final location on the Main Sequence.

Another point of interest is that evolution in the pre-main sequence stage is influenced significantly by variation in surface conditions, unlike the situation prevalent later during the nuclear fusion stages. Consider, for example, that at the very low surface temperatures in the early contracting phases, the major contribution to the opacity in the surface layers comes from something we haven't yet discussed (which is also prevalent in our Sun now), and that is absorption by the H^- ion. This arrangement comes about because hydrogen has space to have an extra electron. The electrons needed to form this ion are supplied by elements with low ionization potential. In order to examine the effect of H^- opacity on the evolutionary path, Iben (1965) presents the following figure. The solid curve is for a mass fraction of metals having 7.5 eV ionization potential equal to $X_M = 5.4 \times 10^{-5}$, whereas the dashed curve is for $X_M = 5.4 \times 10^{-6}$.



Consider now the following plot from Iben (1965), which shows the variation with time t (in s) of several quantities for a star with mass $M = M_\odot$, the surface temperature T_e (in K), the luminosity L (in units of $L_\odot = 3.86 \times 10^{33}$ erg/sec), stellar radius R (in $R_\odot = 6.96 \times 10^{10}$ cm), the ratio of central to mean density $\rho_c/\overline{\rho}$, and mass fraction in the radiative core $Q_{\rm rc}$ (i.e., the ratio of the mass through which energy is transferred by radiation as a fraction of the mass of the star). The maximum and minimum scale limits for these quantities correspond to: $3.58 < \log T_e < 3.78$, $-0.4 < \log L < 0.6$, $-0.4 < \log R < 0.6$, $0.0 < \log(\rho_c/\rho) < 2.0$, and $0 < Q_{\rm rc} < 1$.



It is then useful to follow the Hayashi and Henyey tracks in this plot, both of which are marked.

Recall that on the Hayashi track, T_e remains approximately constant, whereas L decreases.

- Thus, the Hayashi track must be in the region marked above on the plot.
- From the plot, we can see that R is continually decreasing in this region.
- Meanwhile, ρ_c/ρ, the ratio of central density to mean density is initially flat, but begins to increase as matter piles up in the center.
- Finally, the mass fraction $Q_{\rm RC}$ in the radiative core steadily increases, although the core is still convective overall.

Meanwhile, on the Henyey track T_e increases, and L also increases.

- We can see that in the portion marked for the Henyey track, R is still decreasing.
- The ratio of central to mean density ρ_c/ρ shows a large increase as matter gets more centrally concentrated.
- Meanwhile, $Q_{\rm RC}$ is now large enough that the core has become radiative.

Finally, a contracting protostar will become a star only if the temperature in its core becomes high enough to initiate nuclear fusion. Core temperature increases with contraction as long as the gas stays ideal, but the gas also moves toward being degenerate as it contracts. Once degenerate, the temperature no longer increases with contraction. Thus, the temperature must become sufficiently high to initiate nuclear fusion before the gas becomes degenerate.

Consider a star of mass M and radius R. Starting from equation (4.9):

$$T_c = \frac{G\mu_c m_p M}{kR}$$

which assumes that the star is comprised of an ideal gas, *you showed on Question 5(a) of today's worksheet* that

$$T_c = 2.06 \times 10^6\, \mu_c \left(\frac{M}{M_\odot}\right)^{2/3} \rho^{1/3}$$

If, during contraction, the gas becomes degenerate, then the temperature will no longer increase with contraction. By setting kT equal to the so-called Fermi energy which describes a degenerate electron gas, we get a critical density for the onset of degeneracy, and the temperature at which the critical density is reached in the protostar is given by

$$T \simeq 5.6 \times 10^7\, \mu\mu_e^{1/3} \left(\frac{M}{M_\odot}\right)^{2/3}$$

If the temperature for nuclear fusion is 10 million K, you calculated *in Question 5(b) on today's worksheet* that the minimum mass required for a star to form is 0.075 $M_\odot$.