Stellar Evolution - Details

1. Star formation

In order to form stars you need to have the basic ingredients – gas clouds comprised of mainly H, and He. The hydrogen is found mainly in molecular form or as a neutral atom in the galaxy. Helium is not easy to detect, but its abundance is determined from stellar abundances.

These gas clouds are in a state of equilibrium so that they are not prone to spontaneously collapse on their own to form into stars. The internal gas pressure and self-gravity are balanced to maintain them as stable clouds. But of course these clouds have to become stars, so something must push them over the limit where the self-gravity will overcome the gas pressure. What are the conditions needed to collapse a gas cloud? How do you get the Gravity > Gas Pressure?

Such a condition can occur if you get up to a certain mass known as the Jeans Mass

\[ M > M_{\text{Jeans}} = \left( \frac{9RT}{\mu G} \right)^{\frac{3}{2}} \left( \frac{3}{4\pi} \right)^{\frac{1}{2}} \frac{1}{\sqrt{\rho}} \]  

If this criterion is met, then gravity will overcome gas pressure and the cloud will collapse. And of course the cloud can keep collapsing into smaller and smaller fragments (of lower mass) so long as the density is large or the temperature is low.

In the galaxy, a typical interstellar cloud has a low temperature, typically around 10-100 K. The density of the galaxy does vary quite a bit as well. Density can also be influenced by the presence of dust particles, though the amount of dust compared to gas is pretty low. Dust molecules are of course more massive than the usual gas molecules that you find in clouds, and the more dust that is present, the higher the cloud density.

Here are some typical examples for the Jeans Mass:

If T=10 K, and density ~ 1 atom/cc ~ 10^{-21} kg/m^3 then M_{\text{Jeans}} ~ 700 solar masses.

If T=100 K, M_{\text{Jeans}} ~ 22,000 solar masses.

If density is 100 particles/cc, M_{\text{Jeans}} would be smaller.

Basically you have a better chance of forming stars in regions with high densities and low temperatures. Large star formation regions are very well studied. These are the regions with large areas of ionized gas, or H II regions. H II regions tend to have “large” dust concentrations, with the clouds comprised of about 1% dust – yes that is considered a “large” concentration of dust. H II regions tend to be hot beds of star formation in part because of this relatively high concentration of dust. It also helps that there are some catalysts of star formation found in or near these areas as well, such as strong stellar winds or supernovae shock waves which help to induce star formation.
What happens when the gas cloud starts to collapse? Initially the cloud temperatures are around 10-100 K, and the gas is dominated by hydrogen in atomic or molecular form. The contraction leads to a rise in both density and temperature values of the cloud.

From the previous sections of notes, what other thing does density and temperature influence? Opacity! How does the opacity of the cloud change? It goes up! And what does that do? You have to remember what opacity actually is – it is a measure of the opaqueness of an object, or its ability to blocks the flow of energy. And that’s exactly what happens in the cloud – the energy flow gets blocked and the cloud becomes “opaque”.

How long does that take? This would be on about a time scale like that of the dynamical time scale (equation 2-20), which just depends on the density \( \tau_{dyn} \approx \sqrt{\rho} \). This is a pretty long time since at first the density is very low, but as the density increases the dynamical time scale decreases. The effect of the temperature increase on the gas is also important, since it will tend to cause the gases to go from molecular states to atomic states.

At some point the temperature increase will be high enough for the gas to start becoming ionized. The ionization of the gas also helps to increase the opacity which in turn contributes to the ionization (remember, a higher opacity will trap more energy). And when you increase the opacity you increase the temperature, and that increases the ionization and that increases the opacity, and….well, you get the picture.

At this point all of the heat/energy in the cloud is gravitational. That’s just a basic result of gravity – you squeeze something, it gets hot. Eventually the gas pressure will get to the level where it can counteract the gravitational forces and the collapse will slow significantly – equilibrium is approaching. At this point you have a proto-star. The collapse will continue, but it isn’t really a “collapse” since the material isn’t in free-fall anymore. The rate of contraction is no longer measured by the dynamical time scale since that is only valid for free-fall collapse situations. Also some of the energy will be seeping out of the proto-star in the form of heat. The slow loss of energy will help the gravity continue the contraction at a slow but steady pace.

Where is the proto-star on the HR diagram? In a region on the far right side, near what is known as the Forbidden Region. The name may sound ominous, but it really just marks a location where objects are more cloud-like than star-like. In the forbidden region objects are not in hydrostatic equilibrium, and cannot be considered stars.

Proto-stars would be found just to the left of the Forbidden Region, along a boundary line known as the Hayashi limit. The Hayashi limit marks the boundary between proto-stars and “clouds”. And as you’ll see, the Hayashi limit also influences later evolutionary phases of stars.
Proto-stars are still very opaque and have a high opacity. This will tend to cause there to be a great deal of convection within the star, typically going from the center to the surface.

Over time stars will move down a Hayashi track, initially parallel to the Hayashi Limit. As the radius goes down, the luminosity also goes down, but the temperature doesn’t change much. Eventually the stars will get to a point where the change in radius and temperature and luminosity sends them towards the Main Sequence (towards the left).

While the energy generation here is still dominated by gravity and compression, it is possible for there to be some fusion occurring before the star reaches the Main Sequence, though it isn’t significant.

The evolution on the HR diagram depends entirely upon the mass, with the high mass stars following a higher path and a lower path for low mass stars. It will take time before Thermal Equilibrium sets in (remember, that is the balance of energy output and energy production).

Eventually there will be a balance of both thermal and hydrostatic equilibrium – this happens once the star is on the Main Sequence and is a real star!
2. Detecting Proto-stars

The thermal time scale (for the contraction and such) is relatively short, only about 1% of the star’s Main Sequence life time. Of course short lived, high mass stars are in this phase only a very short time (thousands of years), while low mass stars contract for millions of years.

It is usually very hard to spot a star in this stage of their life, due to its short time span during this stage and also due to the cloudy environment such objects are located in. Typically proto-stars tend to be found in dusty environments, and since they also have low temperatures they are usually only visible as infrared (IR) light sources.

Occasionally some stars do things to make their presence known during this phase of their life (before the Main Sequence), such as an outflow of material. The best example of this are the T Tauri stars (described in detail below), in which case it is relatively easy to spot them. But for the most part proto-stars aren’t easy to spot. For proto-stars that do not go through the T Tauri phase, you can only find them using IR telescopes.

We can estimate the amount of time that stars are in this span of their lives. Go back to equation 2-21 (Thermal time scale)

$$\tau_{th} \sim \frac{GM^2}{RL}$$

We also know that the luminosities can be described as functions of their masses, with the luminosities proportional to $M^3$ for low mass stars, and to $M^5$ for high mass stars. Substituting that in the above, you get the relationship that

$$\tau_{th} \sim \frac{1}{M}, \frac{1}{M^3}$$ (for low, and high mass stars respectively)

This also shows that the thermal time scale for contraction is very short for massive star and long for small stars.

As previously mentioned, a proto-star that does make itself known are the T Tauri stars, and they have the following characteristics:

- Irregular variability/brightness
- Found close to nebula (region of gas, dust)
- Spectra has emission features, and produce an excess of IR light
- $T_{eff} \sim 4000$ K (cool)
- Lots of lithium in their spectrum (an indication of young objects)
- Show signs of mass loss, high winds, flares, etc.
- $R \sim 3 \times$ Sun’s radius
- Masses typically only at most 2 solar masses
- Typically found in binary system – seems to help cause bi-polar outflow

The emission lines in the spectra are due to gas around the star, also from hot disks of gas that surround these stars.

Usually in the area of T Tauri stars you would often find H-H Objects (Herbig-Haro).

Notes 5 - 4
About 400 HH objects are known in our galaxy, often near H II regions. They tend to have rather cusp shaped forms. H-H objects are much hotter and denser than their surroundings which allow them to be seen relatively easily.

The “jets” of gas that produce the H-H objects will extend out a few light years out.

Material is ejected from the T Tauri stars at speeds of around 200-300 km/s. While they may look impressive, the amount of material in H-H objects is only a few times the mass of the Earth. They are mainly comprised of hydrogen, and are fairly low mass. The flow of material from the T Tauri stars can occur sporadically, or in multiple outbursts of material.

The T Tauri phase will at most last about 100 million years, which is pretty short for a star’s life. Eventually the disk of material will dissipate and the outflow will stop. And of course the H-H objects will gradually fade from view as well as they cool off.

3. Main Sequence – Middle Age for a star

What defines the Main Sequence? This is the phase of a star’s life where it fuses hydrogen into helium to produce energy. And that pretty much all there is.

While all Main Sequence stars are fusing hydrogen, they are not all using the same means to transport energy through the star. The two energy transport mechanisms are convective and radiative flow. Which mechanism operates and where they operate inside of a star depends entirely on the mass of the star.

The graph shown here indicates the regions of convection from the center to the surface for various masses. For Masses < 0.3 \( M_\odot \), the entire star is convective.
These stars are located very close to where the Hayashi limit intersects the Main Sequence. As you look at more massive stars, convection is found only in layers near the surface. By the time you get to stars that have masses similar to that of the Sun, the mass fraction that is involved in convection is a very small part of the star at the surface (as is shown in the graph).

As you go to higher masses, convection is seen in the cores of many stars, and the fraction of the centers of the stars that are convective gets larger with larger masses. In the highest mass stars, the convection prevents the cores from becoming structured – there is continual mixing so any density variations are wiped out by convection. In low mass stars the cores are thought to be differentiated with the highest density material in the center. For very high mass stars (>20 $M_\odot$) the convection dominates more than half of the mass of the star’s interior.

Another thing that happens with stars on the Main Sequence is mass loss. While this happens in all stellar masses, it is not really important for the small stars. It is most significant for the highest mass (and highest luminosity) stars since this is where the Eddington Luminosity will come into play (equation 3-11). For comparison, the Sun has a mass loss rate of only about $10^{-14} M_\odot$/year, which is a fairly low rate.

Stars can exceed their Eddington Luminosities every so often, but if they do it too much (lose too much mass), they’ll significantly alter their evolution. Of course if they reduce their mass, they’ll also reduce their luminosity so they’ll be less likely to exceed their Eddington Luminosity for long.

Mass loss rates are determined empirically and the following relationship has been derived (though there are other relations from other studies) –

$$M = -4 \times 10^{-13} \frac{LR}{M}$$

Which is in solar masses/year ($L, R, M$ in solar units).

The mass that is most often lost is comprised mainly of hydrogen, so other elements like C, N, O, etc are left behind. Stars that experience extreme mass loss often have their spectra enhanced with these elements. As mentioned, stars can also alter their evolutionary path in weird ways due to mass loss. The most extreme stars that undergo major mass loss are Wolf-Rayet stars.

Wolf-Rayet stars have the following characteristics:

- Temperatures range from 25,000 to 100,000 K
- Mass loss rates around $10^5$ solar masses/year, which can even get up to $10^4$ solar masses/year for short periods
- Velocities of stellar winds range between 800 to 3000 km/s
- Rapid rotation rates of about 300 km/s
- Usually found at upper end of the main sequence (OB types), with luminosities of 100,000 to million $L_\odot$. 

Notes 5 - 6
Emission lines in spectrum, often of a particular type which results in special spectra designations -
  - WN = Nitrogen +helium
  - WC = Carbon+Oxygen+helium
  - WO = Oxygen

Have various amounts of hydrogen in spectra, which indicates how far they’ve gone into the WR phase
Masses difficult to determine, but wide ranges observed in binary systems, from 5 – 77 \( M_{\odot} \), generally around 30 \( M_{\odot} \).

Apart from these guys, most other main sequence stars are very well behaved. They have a range of other characteristics based upon their masses.

High mass stars (10 \( M_{\odot} \) and up)
  - Convection in the core, comprising 30% or more of mass
  - Fuse hydrogen with CNO cycle
  - Can have significant mass loss
  - High Mass, \( L, T \)
  - Short life on main sequence (10’s of millions of years or less)

Intermediate mass (2<Mass<10 \( M_{\odot} \))
  - Core convection is less than 30% of mass
  - Use CNO and PP for fusion
  - Life spans of billion down to 10’s of millions of years

Low mass (0.08 < Mass<2 \( M_{\odot} \))
  - Core is entirely radiative, outer layers are convective (particularly for 0.5 solar mass and less), though higher masses have less convection
  - PP fusion only
  - Low \( M, L, T \)
  - Long life on main sequence of 10’s of billions of years

Brown Dwarf (M<0.08 \( M_{\odot} \), objects not massive enough to be stars)
  - No fusion (though may have some deuterium fusion)
  - More like a planet than a star.

Main Sequence Evolution

On the MS, stars evolve gradually upward, towards the right (higher L, lower T) – this gives the MS width. The HR diagram shown below based upon Hipparcos satellite data has a wide Main Sequence. Since this is based upon relatively nearby stars, the data is rather skewed to medium mass stars, since most high mass stars are rare, and low mass stars are too faint to see.

Theoretical models of stellar evolution also show a wide Main Sequence as can be seen in the H-R diagram on the next page.
So why do the stars evolve in the way that they do?

As stars evolve, their internal structures change. How they change depends upon what is happening in the core, which depends upon how much convection is going on in there. Remember convection is thought to occur in the cores of high mass stars, but not in the cores of low mass stars.

For low mass stars, the core is gradually depleted of hydrogen over time, working from the center outwards. So the amount of hydrogen at any time is lower and lower within the core.

For high mass stars, the hydrogen depletion occurs over a greater area due to the mixing of material caused by convection.

The time a star spends on the main sequence depends on the mass-luminosity relationship. A general formula for this is

\[ \tau_{ms} \approx (M)^\alpha \times 10^{10} \text{ years} \]

Where \( \alpha = -3 \) or -4 (though if you just stick with -3 that is typically a sufficient approximation). The mass is in solar masses.

5. Post-MS Evolution

Once hydrogen is depleted from the core, the only fusion will be in a thin shell around the core. The core of helium doesn’t produce any energy. It is also constant in temperature throughout (isothermal). The mass of the helium core will continue to slowly increase due to the hydrogen shell fusion. This is not a good thing. The inert core has to support the layers above it purely through pressure. And of course gravity is still at work, and this will cause to the core to become compressed – it contracts slowly.
And as you would expect, as the core contracts, it gets hotter. Since no more energy is being produced by the core through fusion, it is no longer in thermal equilibrium (more energy is given off then is produced).

While the core gets hotter and hotter, the hydrogen shell fusion starts kicking into overdrive (it is getting hotter as well). The shell is also out of thermal equilibrium but in the opposite sense – it is producing more energy than it is giving off. This excess of energy production in the shell causes an expansion of the outer layers of the star.

As the outer layers expand, they also cool off. Even though the radius of the star is increasing, the surface temperature is decreasing. The net result is a fairly constant luminosity at first.

At this point, the dominant type of energy that is given off comes from the gravitational contractions. This evolutionary span is known as the Hertzsprung Gap. It is usually very hard to catch stars in this area since they evolve pretty fast during this time,
especially the high mass stars. In large clusters, it is easier to find stars here since there are so many stars. Also in globular clusters, many of the stars currently this phase are low mass, so many more are found in this area in those HR diagrams.

At the end of the Hertsprung Gap, the temperature of the core and fusion shell will continue to go up, which leads to more shell hydrogen fusion. And that produces more helium and increases the growth of the core. Finally thermal equilibrium is restored and the luminosity now starts to increase.

The large cool envelope will be very opaque (it has a high opacity). This will help to trap in heat and lead to a great deal of convection in the outer layers of the star. Some of this convective motion can reach from the surface all of the way into the core. Stars in this phase of their life may experience a “dredging up” of material from the core to the surface. If this happens in a star, then core metal-rich material can be visible in the star’s spectra.

Low and medium mass stars will keep going up the RGB (red giant branch), a path that follows the Hayashi limit. High mass star just migrate towards the right hand side, and generally don’t change their luminosity much. You can see how this path is sort of forced in the way it is going – any further to the right and the star would be in the Forbidden Region, so it can’t go in that direction. Low mass stars will develop a degenerate core during this time, while the high mass stars will not since they generally evolve too fast for degeneracy to set in.

The stars located near the Hyashi limit will continue their upward path until the core temperature reaches a value of 100,000,000 K. That is the temperature needed to set off helium fusion (the triple-alpha process) in the core – well that has been the temperature we have been using for some time, but as I mentioned earlier, it is possible that the triple-alpha process could start at a lower temperature, but we’ll stick with the traditional value for now.

For a high mass star, the core will reach this temperature threshold without the core being degenerate and generally with the star well to the left of the Hayashi limit. But for a low mass star, the core will likely be electron degenerate when it hits this temperature and that leads to the thermo-nuclear runaway ignition of the core (this was discussed back in the notes set 3). This ignition is known as the Helium Flash.

For a star with a core mass of 0.5 $M_\odot$, the helium flash will release energy equivalent to $10^{11} L_\odot$. While this is a very powerful event, it isn’t visible since it is happening deep within the star (in the core). The most significant aspect of the helium flash is that it will cause the core to become “normal” again – the degeneracy is removed, and it behaves like an ideal gas again. This is mainly due to the expansion of the core during the flash. Stars that are less than 2 solar masses are thought to have helium flashes due to the formation of a degenerate core after the end of the Main Sequence phase. The high mass stars will just ignite their helium without any fanfare.