Star Formation

Stars form in cold, dense clouds of molecular gas and dust. These clouds exist in hydrostatic equilibrium--when gravity pushes in, a responding sound wave pushes out. If the cloud is cold and dense enough (i.e., the speed of sound is slow enough), a slight nudge from, say, a supernova, can cause the beginnings of a collapse. A collapsing cloud will typically break apart and form several stars at once.

Empirical models suggest that most stars are above $0.5M_{Sun}$ to begin with. This initial distribution might not line up with what we see in real observations due to the evolution and deaths of stars and systems of stars over time.

Fusion

If protostars gain enough mass, they become dense enough for hydrogen to fuse into helium via proton-proton chain reactions, like so:

$$p + p \rightarrow {}_1^2D + e^+ + \boldsymbol{\nu}^e + 1.442 \text{ MeV}$$

$$\rightarrow {}_1^2D + {}_1^1H \rightarrow {}_2^3He + \boldsymbol{\gamma} + 5.49 \text{ MeV}$$

There are two of these chains, so the overall reaction is:

$$4H^+ \rightarrow 4He^{2+} + 2e^+ + 2\boldsymbol{\nu}^e + 26.73 \text{ MeV}.$$

There's also the "triple alpha" process ($2He \rightarrow Be$, $Be + He \rightarrow C^{12}$) in more evolved stars, as well as the CNO cycle. The CNO cycle has a similar formula to PPCR, but it uses carbon and nitrogen as catalysts for the fusion, generating an oxygen which decays back to carbon to restart the chain.

Stellar Classification and the Hertzsprung Russell Diagram

Stars are very hot objects, and so their radiation spectrum is dominated by blackbody (thermal) radiation. The peak wavelength of a blackbody emitter like a star is given by Wien's Law:

$$\lambda T = 2.898 \text{ x } 10^{-3} \text{ m K}$$

which comes from Planck's Law:

$$P = 2hf^3 / (c^2 * (e^{hf/kT} - 1)).$$

This means we have a relationship between *color* (frequency of light emitted) and *temperature*, which is further related to the flux radiated from the star by Planck's Law and the derived Stefan-Boltzmann Law:

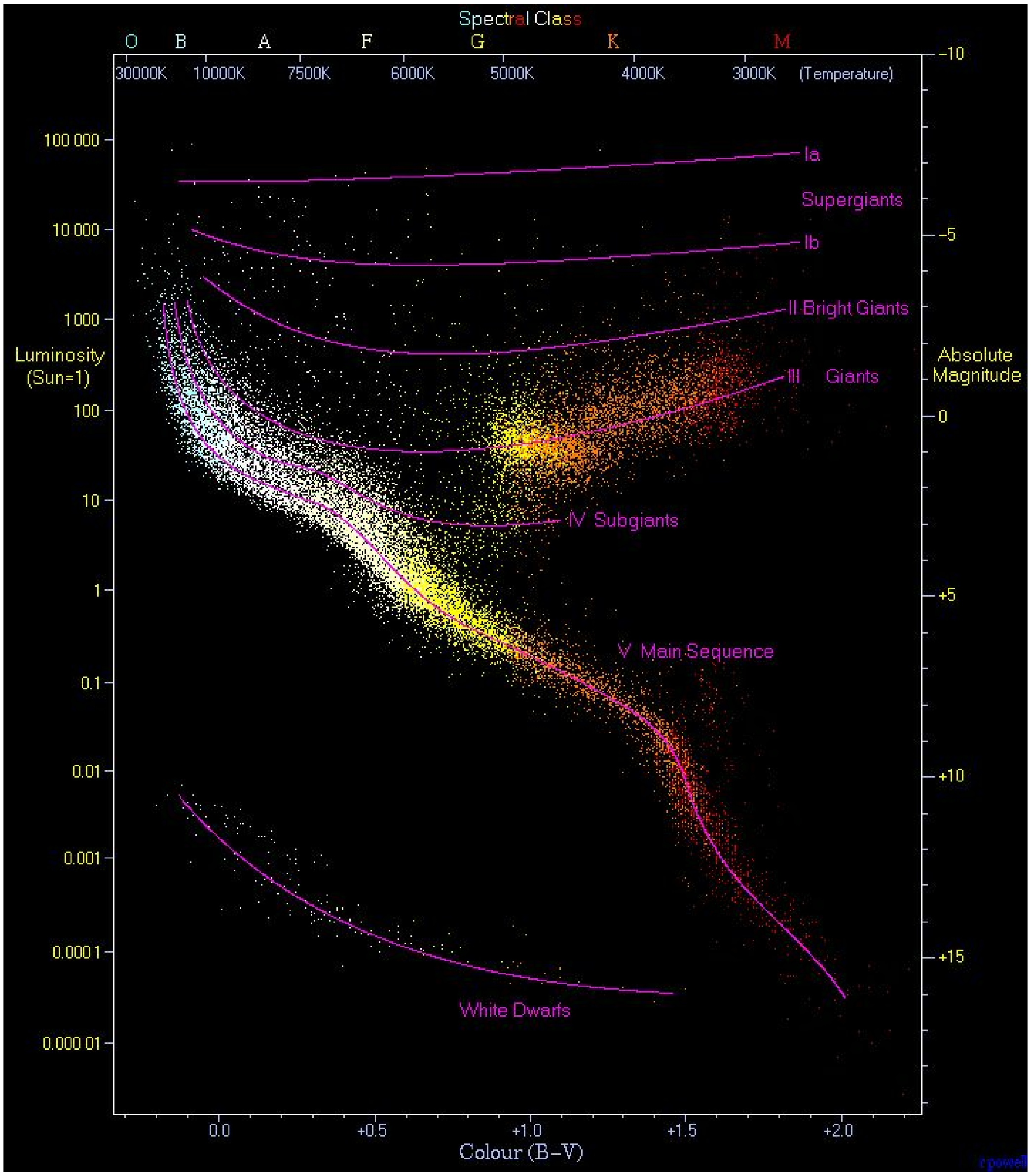
$$F = (5.67 * 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}) * T^4$$

and the flux is just the luminosity divided by the surface area of the star:

$$L = F4\pi R^2.$$

So, ultimately, we can relate the power radiated by the star to its temperature (which is tied to its color). If we plot power versus temperature and color, we get what is known as a Hertzsprung-Russel diagram.

(Note the OBAFGKM spectral classification along the top):



The main sequence line along the diagonal is where a star's life begins. We sometimes call this the "zero age" main sequence (ZAMS), marking the time when the star begins to fuse H into He. That's something of a fuzzy boundary, because stars can be emitting light before that if they become hotter due to gravitational contraction. Normally, the period between protostar and main sequence is short enough that it's a fine approximation. On the bottom right of the diagonal are low-mass red dwarfs. On the top left are high-mass blue main sequence stars leading into blue giants. Our Sun would be right about in the middle of the yellow part of that diagonal line. There's also white dwarfs, which are stellar remnants. We'll go through each class of star in order of mass.

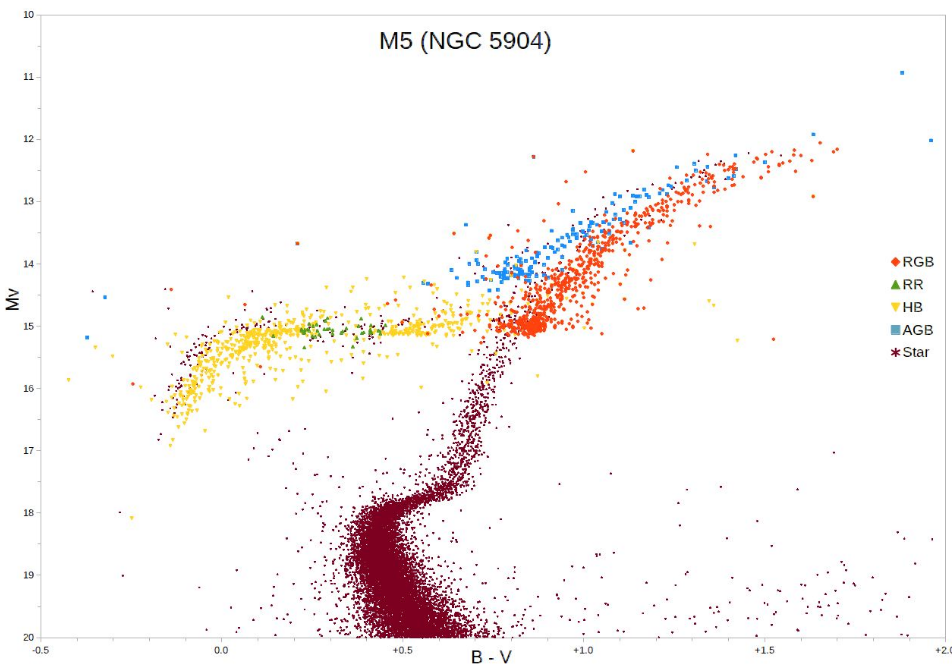
Very Low Mass Stars (.1 - .35M_{Sun}) -- Class M

Stars in this mass range don't ever develop a dense helium core because they are too small for their density to overcome thermal convection, which keeps all the material moving and unable to clump together. Eventually, they'll cool to become white dwarfs, but the Universe isn't old enough for this to have happened yet.

Low Mass (.35 - .6) and Medium Mass Stars (.6 - 10) -- Class K and G

We can see a "knee" in the HR diagram called the main-sequence turn off (MSTO) when main-sequence stars stop fusing hydrogen, cool off, and enter the red giant branch (RGB) as the core contracts and the outer layers expand from radiation pressure. This process is largely the same between low-mass and medium-mass stars, but the lower end may not go through all of the branches (or it may take an exceedingly long time). When the star starts to fuse helium in its core, the cooling pauses and it begins to turn blue, entering the horizontal branch (HB). For our purposes, we need to be careful not to confuse blue stragglers with bluer giants on the dimmer side of the HB.

Once the helium burning stage is done, the star begins to cool once again. The core contracts, the envelope expands, and photons from the helium burning phase can worm their way out and increase the luminosity of the star (it moves up and to the right on the HR diagram). This is the "asymptotic" giant branch (AGB), since it tracks closely with the original RGB. Below is an HR diagram of a GC with the giant branches marked:



Note the "RR" marking. Those are RR Lyrae-type variable stars (interestingly, discovered by Willamina Fleming of the Harvard Computers) which are typically very faint, leading to the so-called RR Lyrae gap in CMDs of globular clusters.

An AGB star begins to lose mass as its distant outer layers are peeled by strong stellar winds, and the core slowly becomes degenerate as heavier elements begin to fuse. If the star began with less than $8M_{Sun}$, the core will contract into a white dwarf and the remainder of the mass will be taken off by winds (a WD can't go above $1.44M_{Sun}$ or it explodes). The 8 - 10 solar mass range would end up as a CCSN instead. Higher than that, and we're getting into true high-mass star territory.

High Mass Stars (>$10M_{Sun}$), Supergiants, and Hypergiants -- Class O, B, A, F

A star with more mass is both more dense and contains more fuel than other stars. This means that it can fuse at a higher rate than lower-mass stars, burn brighter, and consequently die out earlier. Massive stars tend to move off the main sequence quickly. On the very highest end, in fact, they might be over the Eddington limit -- the point where the radiation pressure coming out equals the gravitational pressure pushing in -- although that's a pretty rare case. In general, these stars have very strong winds and lose a lot of mass very quickly.

In terms of their evolution, massive stars start burning helium earlier, and without necessarily having a tightly-condensed core. This means that they don't swing through the various giant stages of a smaller main sequence star, but instead proceed to become supergiants. Red giants tend to be less massive--they have more material in their envelope and are more opaque, so they look dimmer, cooler, and redder. For bigger stars ($40M_{Sun}$ or higher, roughly), they have so much radiation pressure that their envelope is pushed off and they become blue supergiants. In both cases, the core continues to fuse heavier and heavier elements through triple-alpha until eventually it collapses. The resulting explosion destroys the outer layers of the star.