The Life and Times of Stars

1 Birth of Stars

Stars are born out of clouds of interstellar gas, inside the dense cores of molecular clouds. Much of the interstellar gas is warm enough that the gas particles are moving relatively quickly. This quick motion gives rise to pressure, which can counteract the tendency of an interstellar cloud to collapse under its own gravity. However, inside a molecular cloud, the gas is shielded from interstellar radiation that would heat it by the gas and dust in the outer parts of the cloud. As this gas cools off enough, it may reach a low enough temperature that it begins an inevitable collapse under its own gravity.

A part of a giant molecular cloud will fragment as it collapses, with over-dense regions in it collapsing away from each other. Each of these regions goes on to make a separate star. Tens, hundreds, or even thousands of stars may form at once out of a collapsing molecular cloud.

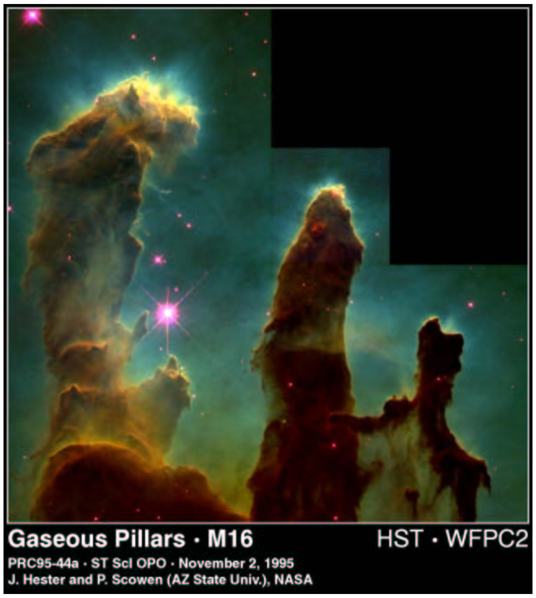

Figure 1: Stars are being born in "pillars" of dense gas in the Eagle Nebula. Inside these, stars form; the radiation from very hot young massive stars then heats up the gas, and when it breaks through the edge of the dense clouds the clouds effectively "boil off".

As the dense regions of the clouds collapse, they come closer and closer together. This releases gravitational potential energy, and the collapsing cores heat up. These collapsing cores become protostars— those things that will one day be stars. The protostars continue to collapse, heated by the gravitational potential energy they are losing as they contract further. The cloud around the protostar, due to its rotation and the dissipation of molecules in the cloud running into each other, collect into a flattened, rotating disk around the star. It is from this disk of material around the protostar that planets will eventually form.

As the protostar collapses, it gets denser and denser. The pressure at the center of the star gets higher and higher, as does the temperature. Eventually, the pressure and temperature get high enough that the conditions become right for Hydrogen fusion. At this point, the star has become a main sequence star.

2 The Main Sequence Life of a Star

As long as a star is “burning” Hydrogen to Helium in its core, it is a main sequence star.

Note: be careful when you read the term “burning”. Used in the context of the cores of stars, we are talking about *fusion*; the release of energy by combining light elements into heavier elements. This is very different from the “burning” you are familiar with from the fires you will see on Earth. That sort of burning is the combination of flammable materials with Oxygen; it is entirely a chemical reaction. In contrast, fusion is a nuclear reaction. Therefore, be aware that when we say a star is “burning” Hydrogen, what we really mean is that inside the star the process of nuclear fusion is using up Hydrogen to make Helium. Similarly, if we say a star is “burning” Helium, we mean that Helium is being combined in nuclear fusion to make heavier elements.

The energy we see radiated from the surface of a main sequence star is the result of that gas being heated by the Hydrogen fusion going on deep in the star. The high-energy photons created in this fusion process do not escape the star directly; the star is opaque to them. Rather, the gas in and around the core of the star absorbs these photons, and is heated by it. These layers then heat the outer layers, and so on and so forth. The outermost layers of the star, though hot by our standards, are much cooler than the huge temperatures at the core of the star.

The star will, over time, burn the Hydrogen in its core to Helium. How long this takes depends on the mass of the star. A more massive star will have more gravity compressing the core, making it hotter and higher pressure, and so will have much higher rates of fusion. Even though a more massive star has more Hydrogen to burn, it generates so much more energy that it uses it up much faster than a lower mass star uses up its Hydrogen fusion fuel. The more massive a star, the less time it spends on the main sequence.

As a main sequence star burns hydrogen, the helium “ash” builds up in the core of the star. Eventually, the star reaches a point where there is not enough Hydrogen left in the core to burn, and to generate the energy and pressure necessary to hold the core up against the crushing gravity that the core feels. At this point, the star has completed its main sequence lifetime.

A star like the Sun will spend approximately 10 billion years ($10^1$0 years) on the main sequence. (The sun is approximately half way through its main sequence lifetime.) A high-mass, 9 $M_\odot$ star will only spend 25 million years (2.5×10^7 years) on the main sequence. In contrast, an 0.5 $M_\odot$ star will spend 80 billion years on the main sequence. As this is older than the age of the Universe, no stars of this mass have yet had time to finish their main sequence lifetimes!

3 Post-Main Sequence Stellar Evolution

When a star no longer has enough Hydrogen fuel at its core to generate the energy and pressure necessary to hold itself up against gravity, the core will start to collapse. This causes the core to become even more compact and even hotter. Eventually, the core will compress enough that conditions become right for other kinds of fusion.

Many stars will next go into a mode of "hydrogen shell burning". In this case, there is an an inert Helium core, packed in as small a space as the electrons in the Helium will allow it to be packed together given the laws of Quantum Mechanics. (Material in this state is known as "degenerate".) This degenerate helium core has enough gravity to pull the gas around the core into a dense spherical shell with the pressure and density necessary for hydrogen fusion. As this hydrogen shell burning progresses, more and more helium ash builds up, until the degenerate helium core compresses enough that Helium fusion becomes possible. At this point, the Helium core swells up very quickly under the influence of the energy generated by Helium fusion. We then have a star which, at the core, is burning Helium to Carbon and Oxygen; outside the core, there remains a shell which is burning Hydrogen to Helium.

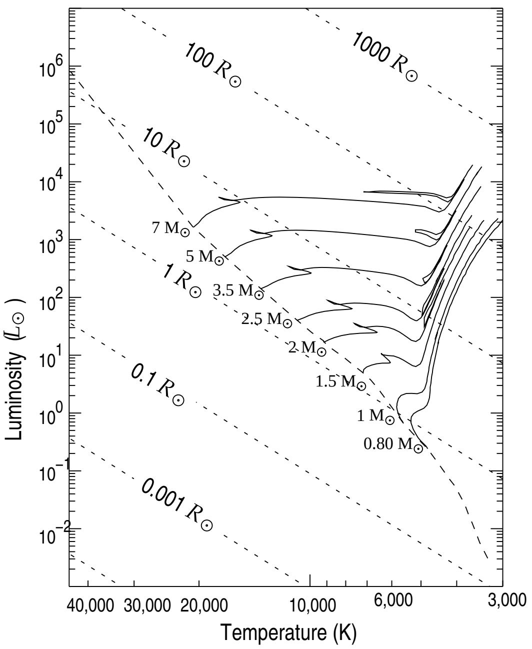

Figure 2: Tracks that stars follow through their evolution on the H-R diagram, starting at the main sequence (dashed line). The solid lines show what happens as they go through their main sequence (burning Hydrogen at their core), and then "leave the main sequence", turning into a red giant (burning hydrogen in a shell around a helium core). (Tracks from the Padova Database.)

More massive stars skip the degenerate helium core step, and go directly to the two-stage core, burning Helium inside the core itself and burning Hydrogen in a shell outside the core. In both cases, outside the Hydrogen shell there is an inert Hydrogen "envelope", heated by the fusion at the core. More massive stars will also progress to fusing even heaver elements. As the products of Helium fusion build up, eventually Carbon and Oxygen will fuse to heavier elements, and so on and so forth. A very well aged high-mass star may have an onion structure, with progressively heavier elements undergoing fusion as you go deeper and deeper into the star towards the core.

All of these post-main sequence stars, with fusion processes other than simply core Hydrogen burning, share one common feature: the core is much more compact than a main-sequence Hydrogen burning core, and as such, they perform their fusion more vigorously. Therefore, the total energy output of the star will, except for the very highest mass stars, be greater than it was on the main sequence. These very compact star cores performing other kinds of fusion besides core Hydrogen burning are also much hotter than main sequence cores. As a result, the outer envelope of the star is pushed out farther by the radiation pressure of the more compact core, causing the total size of the surface of the star to swell. Put these two things together: the star generates more energy— that is, it is more luminous— and it swells to a larger size. At this point, the star has become a giant (or, for the most massive stars, a supergiant). Figure 2 shows the tracks that stars of various masses follow from the main sequence through the end of the Hydrogen shell burning phase of their life. You can see that once they leave the main sequence, they all get larger and congregate in the "red giant" region of the H-R diagram.

Compared to where it was on the main sequence, as a star starts other kinds of fusion at its core, it moves *up and to the right* on the H-R diagram. That is, it moves to higher luminosities, somewhat lower temperatures, and higher sizes. Post-main sequence stars congregate together on the giant branch (as well as other parts variously called the "horizontal branch" and the "asymptotic giant branch") which is easily seen above the main sequence on an H-R diagram of stars in our galaxy. These giant stars are all stars which have completed Hydrogen fusion at their cores, and at their centers are performing Hydrogen shell burning, fusion of elements heavier than Hydrogen, or both.

As a star progresses through different stages of its post-main sequence lifetime— with different forms of fusion going on at its center— it will move up and down (or back and forth, for the most massive stars) this region of the H-R diagram. Always, however, these "evolved" stars are bigger than they were on the main sequence; they are also usually cooler and more luminous than they were on the main sequence. The post-main-sequence lifetime of a star is typically only about 10% of its main sequence lifetime. Once an old star leaves the main sequence, it's most of the way through its life as an active star.

4 The Endpoint: Low-Mass Stars

A "low-mass" star in this context is a star which is less than approximately eight times the mass of the Sun. The Sun, therefore, is a low-mass star. These low mass stars all share a similar fate. They will burn Helium to Carbon and Oxygen at their cores, but will never generate the pressures and densities necessary for Carbon and Oxygen fusion.

In the very late stages of the star's lifetime, an extremely dense degenerate Carbon and Oxygen core builds up at the center. (Remember, a degenerate core is where the nuclei and electrons are packed as close together as the electrons will let them be packed.) This core might have approximately half of the mass of the Sun, but be about the size of the earth. In shells outside this core, Helium burns to Carbon to Oxygen, and Hydrogen burns to helium. The cores that build up are so dense that the gravity pulls these shells very close, causing very vigorous fusion. This in turn pushes the outer layers of the star to a very huge size. The Sun, for example, at the end of its life, will eventually reach a size that is a couple of hundred times its current size; it will be close to 1 AU in radius! A swelling star at this late stage in its life is said to be on the "asymptotic giant branch" (AGB).

Naturally, as the star gets so large, the surface gravity of the star gets much smaller, because gravity drops off with distance. Eventually, the star reaches a state where it loses its grip on its outer layers. Relatively small changes in the compression of the core can cause relatively large changes in the rate of fusion (and therefore in the energy generated), causing the star to push away the outer layers of the star now only tenuously held by gravity. These outer layers of the star form an expanding shell of gas around the star, that gets less and less dense as it expands out in space. Left behind is the very intensely hot core of the star. At this point, the star is a "post-AGB" star. The intense ultraviolet radiation from the very hot stellar core ionizes the thin expanding gas shell around the star. We observe these expanding gas shells around the hot post-AGB star as a planetary nebula.

The planetary nebula will continue to expand, and will shine fairly bright as it is large and has a large emitting area. However, it also gets large enough to be transparent, and we can see the hot central star. Eventually, over the course of tens of thousands of years, the planetary nebula will expand out and merge with the interstellar gas, joining gas clouds perhaps to participate in a new round of star formation. By times time, the post-AGB star at the core will have finished its last final bits of fusion, and will be a white dwarf— a degenerate Carbon and Oxygen star, usually about half the mass of the Sun (but sometimes found up to 1.4 $M_{\odot}$), still very hot but not generating any more energy. As it radiates, it cools off. White dwarfs star below and to the left of the main sequence on the H-R diagram. They are extremely hot, but because of their very small size they are not especially luminous. As they cool off, they move down and to the right on the H-R diagram. Their size does not change very much, but as their temperature goes down, so does their luminosity.

Eventually, the white dwarf will cool off to become a dead stellar remnant. A rare white dwarf may still have some action in it yet; if it has a companion, there is a chance it will become a nova, or even a Type Ia supernova. However, that is a topic for another day.

Some stars of intermediate mass— up to about 8 $M_\odot$— may actually get hot and dense enough at their cores to fuse Carbon and Oxygen to even heavier elements. These stars, which are much more rare than lower-mass stars, may leave behind white neon-oxygen white dwarf stars instead of the much more common carbon-oxygen white dwarf stars.

5 The Endpoint: High-Mass Stars

If a star masses more than 8 $M_\odot$, it has a much more exciting end in store. These stars have enough mass to compress their cores to support fusion of successively heavier and heavier elements all the way up to iron. However, once these stars start to build up iron in their core, they can't do anything more. It actually *costs* energy to fuse iron to heavier elements. Once a high-mass star starts to build up an iron core, it can no longer generate energy at its core to support itself. For a time, the "electron degeneracy pressure" of the iron core can support the star. The iron core is packed together as closely as its electrons will allow it to be packed— just like the degenerate helium core of a lower mass post-main-sequence store, or the degenerate Carbon and Oxygen core of a low mass AGB star. Outside the iron core, Silicon fuses to Iron. As this happens, the size of the iron core builds up.

Eventually, the iron core reaches a mass where even electron degeneracy pressure cannot hold it up against the incredible force of gravity. This limit, known as the *Chandrasaekar Limit* after the scientist who first calculated it, is about 1.4 $M_\odot$. When the degenerate iron core reaches this size, even electron degeneracy pressure cannot hold it up against its own gravity, and all of a sudden the core will collapse. Electrons are "pushed into" nuclei— electrons combine with protons to make neutrons (and neutrinos). The core shrinks incredibly, from the size of the Earth to a mere 10km diameter. At this point, the star is the density of an atomic nucleus, and the *neutrons* are packed as closely together as they can be! Now, rather than electron degeneracy pressure holding up the star, neutron degeneracy holds it up. This neutron degeneracy pressure stops the inward fall of the star. All of the material outside the neutron core either collects on the star, or "bounces" in a massive rebound. All potential energy released as the core collapsed to that much smaller size is released in a "core-collapse" (or Type II) supernova. A shockwave is driven out from the center of the star to the outer layers of the star, blowing the outer layers of the star away in a truly massive explosion.

A high-mass star, once its life is complete, leaves behind a supernova remnant— the shock of the explosion blowing the envelope of the star outward, plowing into the interstellar gas— and a neutron star. That neutron star may have a very intense magnetic field, and if it is rotating, we may observe it as a pulsar (also a topic for another day).

The very most massive stars, during their final core collapse, may in fact collect so much mass into their cores that even neutron degeneracy pressure can't hold them up. In this case, *nothing* can stop the collapse of the core of the star. The core will collapse to a black hole, effectively having left our Universe altogether, leaving behind a black hole event horizon, one of the most truly bizarre objects found in astrophysics, and, you guessed it, a topic for another day.

6 Clusters as Snapshots of Stellar Evolution

As was stated above, stars tend to form in clusters. A cluster of stars is a group of stars that formed all at the same time. However, even though stars all formed at the same time, they won't all die at the same time. The more massive stars life their lives much faster, using up their Hydrogen fuel at a greater rate than less massive stars. This means that more massive stars will leave the main sequence and become giants first. Not too long after they have left the main sequence, they will die altogether. The first stars to die— the most massive ones— will go supernova. Eventually, stars of too low mass to supernova will die, leaving behind white dwarfs.

By looking closely at the H-R diagram of a cluster of stars, we can figure out its age. We can track how far up and to the left the main sequence extends for a star. We will find a temperature and luminosity that corresponds to a *highest* mass that is still on the main sequence. The age of the cluster, then, is the age where stars of any higher mass will have left the main sequence, becoming giants and dying. Any cluster of stars will show a *main-sequence turn-off*, which is characteristic of its age (see Figure 3). A very young cluster will have a very blue main-sequence turn-off, as only the most massive of stars in that cluster will have had time since the birth of the cluster to leave the main sequence. A very old cluster may have a main sequence turnoff that corresponds to stars even a little bit less massive than the Sun.

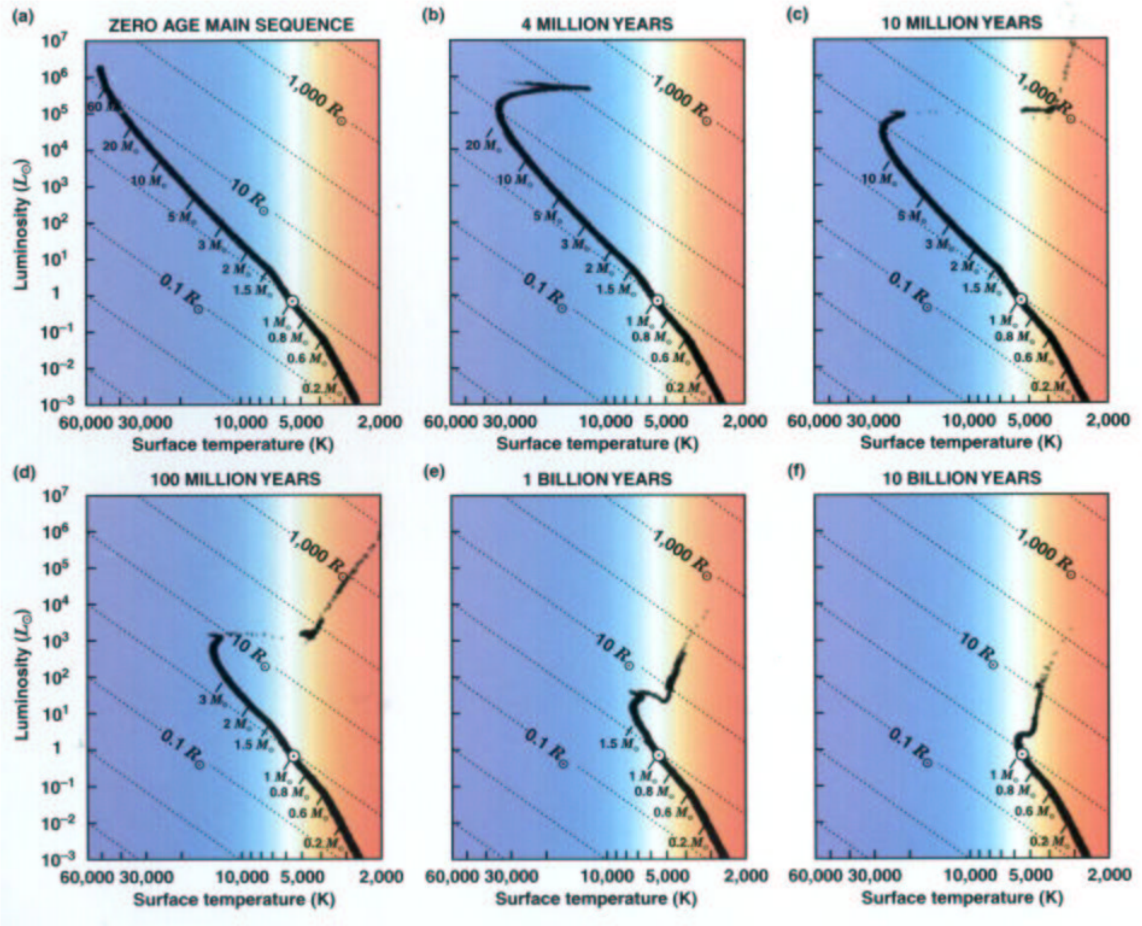

Figure 3: H-R diagram of a cluster at various different ages. The "Zero Age Main Sequence" plot (upper left) shows when the cluster has formed and the stars have just reached the main sequence. As time goes by, more massive stars leave the main sequence and become giants, and then die, first. The "main sequence turn-off" is the point along the main sequence that corresponds to the most massive star that has not yet had time to leave the main sequence and become a red giant.