How Stars Age

Stellar evolution is the process that a star takes as it changes over time. Some stars can take up to trillions of years to complete the cycle which is longer than the universe has been around, while others can take as short as millions of years. A star begins to form when dust and gas get compressed by the influence of gravity. As it gets more and more compressed, it heats up and the center of the ball of gas gets very hot until it reaches around 18 billion degrees Fahrenheit. Because the temperature is so high, nuclear fusion can occur making the elements heavier, releasing energy which follows outwards from the core of the star which produces light, eventually causing a star to be born. Most of the time stars form in star clusters. Stars that are not formed in clusters usually fade away due to the lack of gravity until they find an orbit. Once formed, the outward force of fusion is balanced with the inwards force of gravity where it stays like this for most of its lifetime (About 90% of its lifetime). Massive stars do not live nearly as long because they have a lot of gravity making their core a lot hotter, eventually burning through their hydrogen atoms a lot faster. When stars start to die away, their gravity is still intact, however, the outward force of fusion begins to slow down. It is at this point in the star's life cycle where the mass of the star determines what happens next in its life.

Low mass stars:

As stated before, lower mass stars start to form inside a nebula which is basically a cloud filled with particles (as seen below).

And once the particles start to gravitate towards each other, it forms a protostar which is just a bright glowing area. A protostar does not do any type of fusion because it is not hot enough, so it is essentially just a transition point into the next phase. The next step is it turns into a main-sequence star and does hydrogen fusion, the nuclear fusion of 4 hydrogen protons to form a helium-4 nucleus. This is the state in which our Sun is in right now. Once the hydrogen runs out and the star accumulates enough helium, the low mass star starts to do helium fusion and gets fused to carbon, which is higher energy. It can do this through a process called Triple-Alpha

Process. Because the temperature is so high, 2 Helium molecules can collide to form a very unstable form of Beryllium which only lasts for a split second. However, in that split second if and another Helium molecule comes and collides then it forms Carbon. This causes it to swell up to a red giant (as seen below).

Once that happens, the fusion stops but the gravitational force does not, so it collapses the star and the otter layers of gas start to fade away in different colors.

In the middle of the cloud (planetary nebula), a white dwarf is formed at the core which is extremely dense and made of just heat. These white dwarfs can be found in the bottom left region of an H-R diagram. Finally, after a long wait, the star turns into a black dwarf which is just a cold dead mass of carbon.

This entire process takes billions of years to occur and stars that we know of still have millions of years left in their cycle. Even some low mass stars such as red dwarfs can take up to trillions of years.

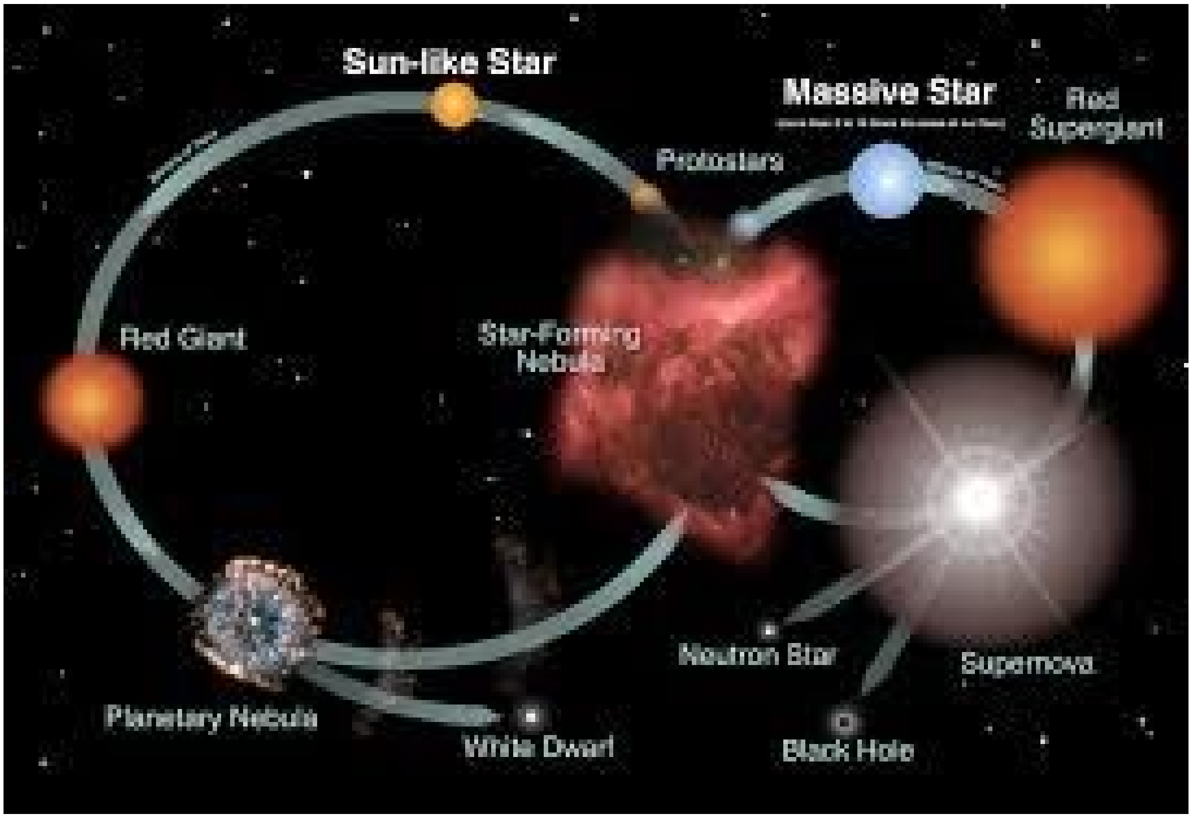
High mass stars:

High mass stars are at least 8 times the mass of our Sun. Just like the low mass stars, it starts to form in a nebula, then transformed into a protostar, then due to hydrogen fusion, it forms into a high-mass star. After millions of years and once enough helium has been acquired, the star will also start to do helium fusion and soon form into a supergiant. This star is extremely massive so the gravitational forces of this star are trying to collapse the star. To prevent the star from collapsing, the star does fusion at an extremely high rate to counteract the inward force of gravity. Because of this, this star is extremely bright, as, at this point in its life, it is found in the top region of the H-R diagram. Once the mass isn't big enough, the star collapses down and causes a supernova explosion (as seen below) that rebounds explosively all happening in a fraction of a second.

Supernova explosions are a key part of creating life. It does something called explosive nucleosynthesis, creating heavy elements explosively, which forms new elements such as phosphorus and nickel. It then gets shot outwards into space and can collide with other particles to create planets and life that we know of today. This explosion is stopped by neutrons in that star and it condenses all the way down into this neutron star.

A neutron star is so dense that one cubic centimeter of neutronium (part of a neutron star) has a mass of 400 million tons. However, a more massive star will overcome that stage and keep condensing down into a black hole which is a region where gravity is so strong that light or anything else can not escape from it.

As seen in the image below, all stars start off forming the same way (inside a nebula). However, after a certain point, massive stars take a different part and the end of their cycle is much different. Also, the amount of time both cycles take is completely different.

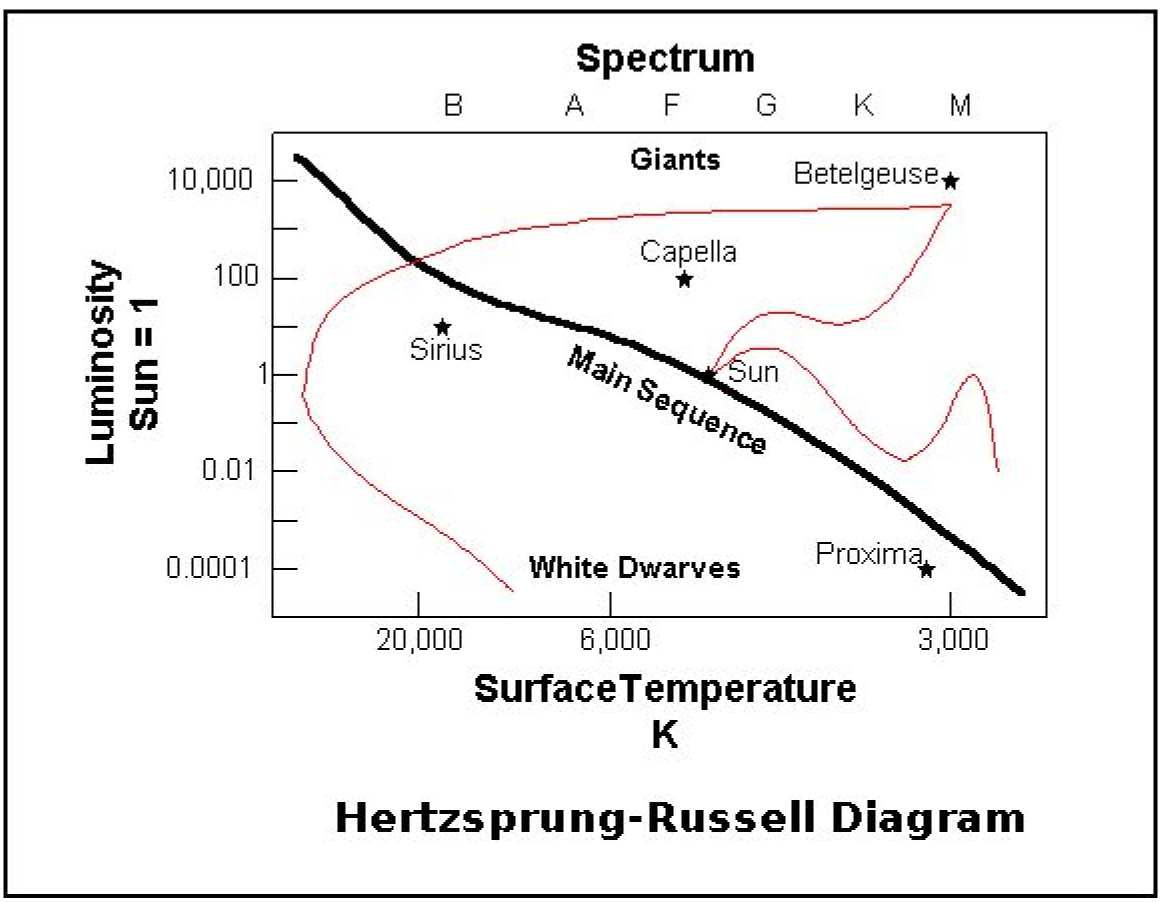


H-R Diagram

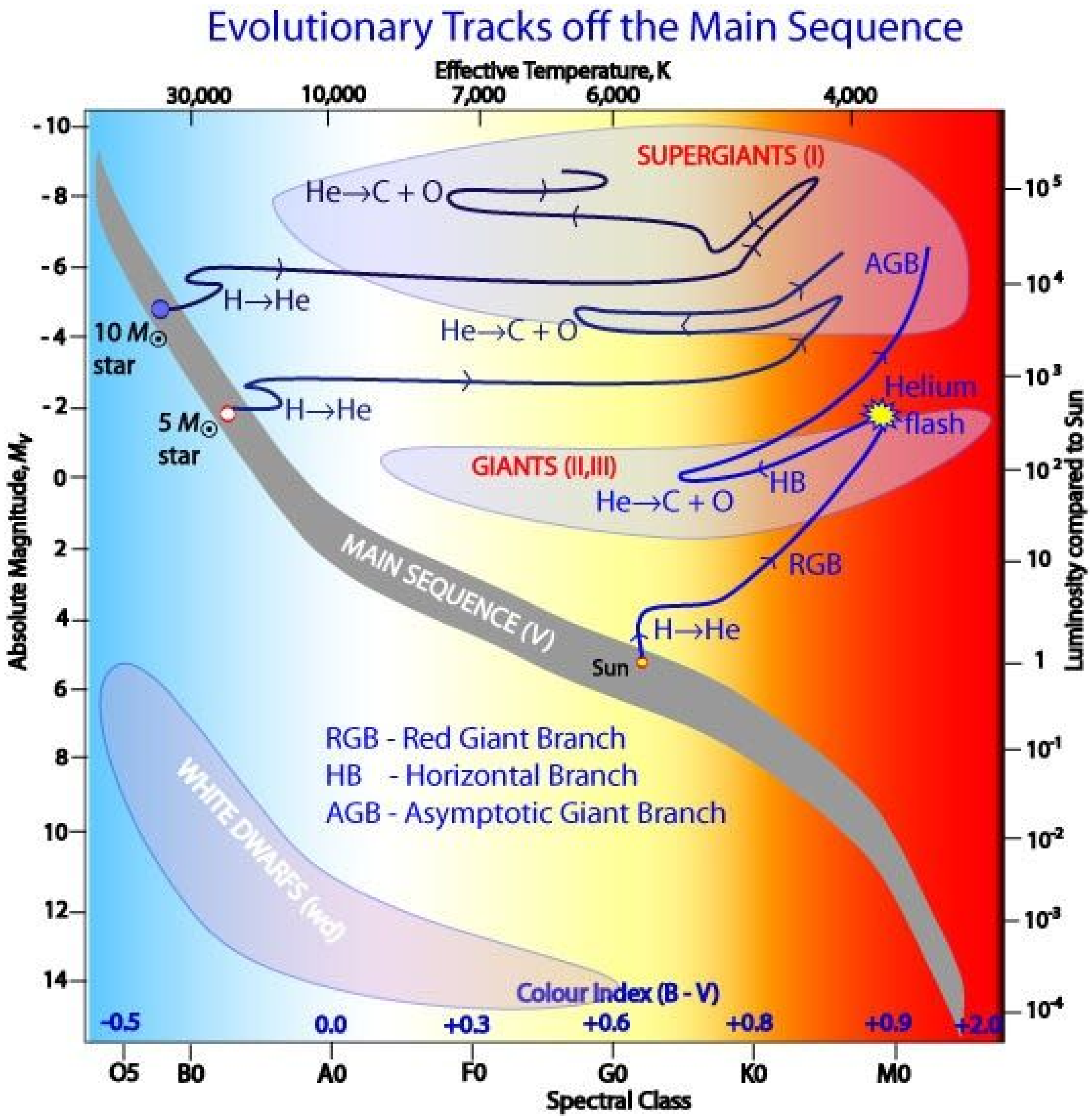
When a star is doing hydrogen fusion, it appears on the main sequence (or zero-age main sequence - ZAMS) for about 90% of its lifetime. The stars on the top left of the main sequence are brighter, have a high fusion rate, and have a lifetime of about 10 million years. The stars in the middle (like our sun) have a medium fusion rate and live for about 10 billion years. The stars on the bottom right of the main sequence are extremely dim, have a low fusion rate, and have a lifetime of about 1 trillion years. A little bit to the right and slightly brighter are the Red Giants, and above them and even more luminous are the Super Giants. And finally on the bottom left are the white dwarfs which are extremely hot and dim.

Low/Medium Mass Stars:

As the cloud of dust and gas collapses its luminosity drops making the star fall onto the main sequence. Here, since the temperature and pressure are high enough that hydrogen fusion starts to occur in the core and stabilizes it on the main sequence for billions of years. Then once hydrogen fusion cannot occur anymore, the core collapses and turns gravitational potential energy into thermal energy which causes the photosphere to heat up and expand. The luminosity increases at this state because the star becomes larger, but the temperature cools slightly because the photosphere expands. The path that the star takes on the H-R diagram is called the Red Giant Branch (RGB). The star is now in the red giant stage because the star is fusing Helium into Carbon, Nitrogen, and Oxygen. After the Helium fusion has completed (which can take anywhere from a few thousand years to 1 billion years), the core collapses which again causes the star to heat up and expand causing the luminosity to increase. But quickly after that, the star's outer layers are blown off and a planetary nebula has formed. Finally, it reaches the white dwarf stage where it gets really dense (which makes it extremely hot) and dims. After 10-100 billion years, the white dwarf will become a black dwarf and will not emit enough light to be seen on the H-R diagram. The red line below is the path that I explained a low/medium mass star takes on an H-R diagram.



The picture below highlights the different branches that a low-mass star will take on an H-R diagram as well as the fusion that is occurring at those states as described previously in this paper. As stated before the path that a star takes after burning all hydrogen into helium is the RGB. It is here that the star begins to cool and expand as the hydrogen shell starts to burn. It continues on this branch until the helium flash. The gravity versus thermal pressure at this moment is not balanced. Gravity kept pushing the core in making it denser. However, the core does not collapse due to the repulsive force of electrons. So here the thermal pressure pushing back and the gravitational energy pushing in is not balanced. Because of this, a sudden radiation of heat is rushed from the core outwards until the balance is reached and the repulsive force of electrons is not strong enough to stop the gravitational force. This process lowers the energy released outside to the outer layers hence causing the star to shrink in size. It is at this point when the star again stabilizes on the Horizontal Branch (HB), burning helium into carbon until it cannot do this process any longer. This is like the “second” main sequence stage, however, the process is done a lot quicker as the star is at a much higher temperature. It usually takes only 50 million years. For larger stars, it can take as little as 10 million years and for smaller stars, it can take longer than 50 million years. Eventually, the entire core turns into Carbon. The heat generated by the gravitational potential energy turning to heat fuels the helium and hydrogen burning shell around the core. Due to this, the star begins to expand again, increasing the luminosity and decreasing the temperature. Because of this, the star begins to climb up the H-R diagram on what’s called the Asymptotic Giant Branch (AGB). At this point, solar winds start to pick up, and because the outer layers of the star are so far from the core, the gravitational force is not as strong causing the star to lose about 25% of its mass.



High Mass Stars:

High mass stars start to form in a cloud that is much more luminous than low mass stars. Then, similar to low mass stars, the cloud collapses, and the star stabilizes on the main sequence doing hydrogen fusion for a much shorter time (around 10 million years). Once hydrogen fusion cannot occur any longer, the star also expands and cools, but this time it becomes into Red Supergiant. Since the star can reach higher temperatures due to its higher mass, it can fuse elements up to iron. It stays in this stage anywhere from a few hundred thousand years to 1 million years. After the fusion has completed, a supernova occurs. However, when that happens, the collapse is so massive that the core heats up to 1 trillion K and the luminosity reaches 100s of billions of times of one of a main-sequence star, so this process does not usually appear on the H-R diagram. And then, the core of the star is now a neutron star which is too small to be seen on the H-R diagram, and just like the white dwarf, it gets cooler and cooler and fades away. If the mass is great enough that a black hole is formed, that is not seen on the diagram because it is not bright enough. As seen below, the path that a high mass stars take is different compared to a low/medium mass star.

H-R diagram of a massive star's evolution