# Stellar Evolution

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**What's covered here:**

- What causes stars to eventually "die"?
- What happens when a star like the Sun starts to "die"?
- What happens to the Earth when the Sun starts to "die"?
- What is the final fate for the Sun and other low mass stars?
- What is a nova?

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Stars spend most of their lives on the Main Sequence with fusion in the core providing the energy they need to sustain their structure. There is a price for this. As a star burns hydrogen (H) into helium (He), the internal chemical composition changes and this affects the structure and physical appearance of the star. The older the star, the greater the amount of helium in the core.

The Sun is currently not on the ZAMS, since it has been burning hydrogen into helium for about 5 billion years. This is one of the reasons that the MS appears as a wide strip when it is plotted up. Most of the stars have been doing fusion for some time, and therefore altering their internal structure, such that they are removed from the ZAMS (since the internal changes effect their appearance - their luminosity and surface temperature).

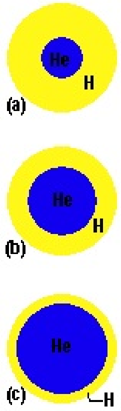


***Figure 1.*** *The core of the Sun (and other stars) over time. The top shows how it started out, with 70% H and 27% He. Over time the size of the helium core increases, so that it gets larger - as shown in (b), and larger - as shown in (c). Remember, this is just the core of the star, while the rest of the star keeps pretty much the same composition while on the Main Sequence.*

The Sun and most other stars originally have a composition of 70% hydrogen and about 27% helium in their cores. This is sort of the standard composition of stars like the Sun, at least when they start out their lives. This is also the current composition of the layers outside of the core since there is no fusion going on out there, but in the core things have changed. Now if you were to look inside the Sun's core today, you would see that there is about 35% hydrogen and 62% helium. Helium is denser, so it sinks to the center of the core. What does it do there? Nothing but take up space. Actually, you can think of helium like a lazy roommate - just sitting around in the middle of the house, doing nothing and getting bigger each day. Actually, that would be a pretty gross roommate, but you get the idea.

The helium core is getting larger every day, since the helium that is produced in the fusion process is just taking up more and more space, since it can't really do anything else. If you think this is bad, you're right. The helium, just by its presence, is sort of crowding out the area of energy production. Remember, fusion can only occur in the hot, high density area of the core. Outside of this area fusion (and energy production) will not be happening. With helium taking up more and more space, there is less space to go into the production of energy. In a way, the burning region is being forced outward away from the star's center, it's getting crowded out by the helium.

What is it like as you get further from the core? It's cooler and less dense (remember those temperature and density graphs from the previous set of notes?). This is a region that is not hot enough to sustain the same rate of energy generation as in the hot, dense core. Is that important? Of course it is important - the energy from fusion helps to hold up the outer layers of the Sun and maintains the various forms of stability within the star (like hydrostatic equilibrium and that other stuff).

What happens when the upper layers are not being held up as effectively as before? Gravity raises its ugly head, and boy does it have one ugly head. You have to remember that gravity is always there, but when you are not fighting its influence very effectively, you pay the price! The layers outside of the core would start to pull inward, and the Sun's core and the area around it would slightly contract. While this might not seem like a good thing, it actually is, since the contraction will help to heat up the area around the core and get the temperature and density to go up to a level where fusion can start in regions that were previously too cool or too low density for fusion to operate.

The basic upshot of this whole thing is that the burning region (energy production region) of a star is gradually moving further out from the center of the star as the fusion by-product (helium) is taking up more and more space in the center.

Does this mean that the Sun is getting larger? No, because you have to remember that the mass of the Sun has been going down steadily over the years, since all the energy that it gives off as sunlight was actually mass at one time. The Sun is losing mass steadily by just giving off light - a lot easier than Weight Watchers, isn't it? Helium is denser than hydrogen, so the core is actually getting slowly denser with more and more helium being produced.

The slow squeezing process seems to have solved the energy problems of the Sun, right? A little more helium causes the energy production region to be slowly pushed out from the center - so everything is just fine, right? Not really, since the Sun (and stars like it) can only do this for so long. Eventually it will get to the point where the contractions will not be able to heat up the interior regions high enough to enable them to produce energy to sustain hydrostatic equilibrium. Even though there is gravity keeping things hot and dense, it won't be enough to help the situation. There is a limit to how tightly you can squeeze stuff and how hot you can get the material.

At this point hydrogen burning in the core is no longer significant, and there is only a thin shell of hydrogen burning around the large helium core. The star is pretty much at the end of its Main Sequence life.

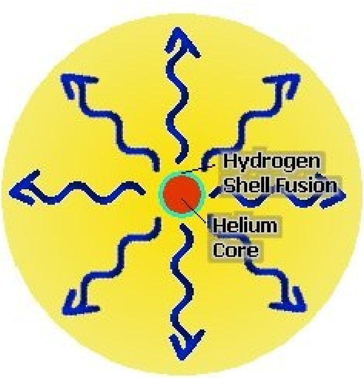


***Figure 2.*** *The outer layers of a star (like the Sun) get pushed out by the compression and heating of the core. Even though there isn't much fusion going on, the gravitational heating of the core causes the heat flow to increase and the outer layers of the star to swell up.*

The **shell burning** of Hydrogen doesn't produce a lot of energy, so it isn't really helping in holding up the outer layers of the star. Yet the outer layers are being held up - how? It is pretty much due to all of the hot gas in there, or **Thermal Energy**, which is just the heat produced by the squeezing of the core. Remember the influence of gravity - it will compress and squeeze the core so that the core gets smaller and hotter. The heat of the core is so great that it will start to actually overdo the "holding up the outer layers" bit. It will, in fact, sort of puff out the outer layers of the star. As the outer layers spread out, they will cool off and the observed surface temperature of the star will decrease. What do we have here? We get a **Red Giant** - better start a new section.

## Red Giants

Finally we get to the red giant stage; I know you have been waiting for this for some time, so just try to stay calm. First, some clarification: I know that red giants are a bit confusing since there seem to be two opposite things happening at the same time - the core is getting smaller and hotter due to compression, while the outer layers are getting more spread out and cooler. You sort of have things going in two opposite directions - but these things are related. Without the heating of the core, there would be no expansion of the outer layers.

In the case of the Sun, it will expand to a size greater than that of Mars's orbit, or become about 430 times larger than its current size, and will have a surface temperature of 3500 K and a luminosity that is 20,000 times its current value. Of course, the core temperature will be increasing (remember, the squeezing is still going on), getting closer to around 100 Million K. The size of the Sun will be as big as the size of Mars's orbit? What will happen to the Earth? - nothing good, obviously. The Sun will get larger and larger each day, and the luminosity will increase, so the surface temperature of the Earth will rise (this is a really big time global warming event). Eventually, after all life on Earth is destroyed by the intense heat and radiation, the planet will enter the expanding outer layers of the Sun. If it doesn't burn up right away, it will probably spiral in toward the center of the Sun, so it will eventually burn up. I guess not even SPF 40 will help at that point. Not only will this happen to the Earth, but Mercury, Venus and Mars will most likely share this fate. Jupiter and Saturn may be the safe places to be at this time, so you better buy some real estate out there now while the prices are still low.

The core is being compressed continually, getting hotter and hotter as well as denser and denser. Is there no limit? Will it ever end? Yes, it will end; there is a limit. The limit comes about due to some of the laws of quantum mechanics. One of these laws tell us how tightly we can pack things in, such as atoms and electrons. Once a star's core gets to the point where the electrons are packed in as tightly as possible, the material is said to be **electron degenerate**. The core of a red giant is therefore becoming more and more electron degenerate. One of the unusual properties of electron degenerate material is that once it is electron degenerate, you can't make it any denser. No matter how hard you squeeze and compress it, it will not get any denser - it will get hotter, but not denser.

Another thing that happens with a red giant is that the outer layers become very convective. Actually, there are huge convective bubbles reaching down all the way to the core and then back up to the surface. For a star that is as large as the size of Mars's orbit, these are some seriously large bubbles! One neat aspect of these huge convection bubbles is that they can mix up material really nicely. Sometimes they can even pull some stuff from the core onto the surface. Red giants can have rather peculiar chemical compositions in their surface layers, since the high density stuff in the core can get mixed in with the material in the outer layers, which we can see when we obtain a spectrum. This is something that astronomers have seen with red giants, and is a feature that is predicted by our computer programs as well.

It's time to get back to the core. When the core temperature reaches 100 million K, it is hot enough for helium fusion to occur. Believe it or not, this is a good thing. Actually, it isn't so good at first, since the core of the star is electron degenerate when the helium ignites, and the resulting ignition is a rather catastrophic event. This **Helium Flash** marks the rapid onset of helium burning in the core for a low mass star. A helium flash is a rather violent explosion that can significantly alter the internal structure of a star, in part because the material in the core is so electron degenerate. We can't actually see the helium flash, since it is buried deep in the core, and it happens relatively quickly, but it does get the star back on the fusion track. Stars more massive than the Sun usually don't have an electron degenerate core, so when their helium ignites it's no big deal. In the case of the low mass stars, the helium flash also has the added bonus of removing the electron degeneracy in the core.

Now we have sort of a happy star - it has gotten its second wind. The helium fusion is making a good amount of energy in the core and the core is no longer electron degenerate. Unfortunately, the helium burning is not as energy efficient as hydrogen burning, so you get less bang for the buck. You might want to think of it as a lower quality fuel, perhaps a lower octane than hydrogen fusion. The basic upshot is that not as much energy is produced in each helium fusion reaction as was produced in each hydrogen fusion reaction, so the star has to burn the helium faster to produce a sufficient amount of energy. The core is still extremely hot, so it is producing a lot of thermal energy as well, which will keep the outer layers puffed up, so the star is still a cool red giant.

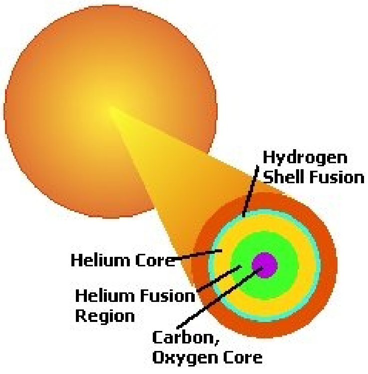


***Figure 3.*** *The interior of a red giant after helium fusion starts. The size of the star is on the order of a couple of hundred A.U.s, while the core is only about as large as the Earth. The close up for the core shows that multiple layers exist. At the center are the by-products of the helium fusion - carbon and oxygen. Above that there is a layer of helium that is undergoing fusion and another layer of helium that isn't fusing (too cool or low dense). Above the helium layers is the layer of hydrogen fusion in a very small shell. This layer marks the outer edge of the core. The rest of the star is for the most part the same composition that the star had to begin with (mainly hydrogen and helium).*

Now helium fuses into carbon (C) and oxygen (O) through what is known as the **triple alpha process**. This is sort of a silly sounding name, but it comes from the old fashioned name for helium (alpha particle), and when you combine three helium atoms together, you make carbon (as well as energy), while four helium atoms will combine to make oxygen (and energy). I guess it could be called the quadruple alpha process, but that isn't as easy to pronounce. Any ways, let's get back to the fusion of helium. Helium fusion is less efficient than hydrogen fusion, so it goes pretty fast and the carbon and oxygen will start to take up more and more space in the core of the star. Does this sound familiar? It should. Again, the burning will move out further and further away from the center of the star and the core will start to get degenerate again. As new regions of helium start to burn, the star can experience **Helium Shell Flashes** (also called **thermal pulses**). These are similar to the explosive helium flash, but less powerful since less material is involved and it isn't as degenerate as the core was when the helium flash occurred. These helium shell flashes are rather troublesome, though, since they do release a fair amount of energy - kind of like violent, uncontrollable hiccups.

After about 1 billion years (for stars similar to the Sun), the build up of carbon and oxygen in the core will prevent the production of a significant amount of energy, since the darn carbon and oxygen are taking up so much space. This marks the end of the line for the star. The core will start contracting, but the contraction will not produce high enough temperatures or densities to ignite the next fusion process. A star will spend only about 10% of its life as a red giant - not much for a second lifetime, but you take what you can get.

Is the end of helium burning the end for all stars? No, stars more massive than the Sun may be able to continue into the next burning stages once the helium fusion stage stops. Remember, more mass leads to more gravitational pull (or contraction), which leads to more squeezing of the core. More squeezing leads to higher temperatures and densities. For these larger mass stars carbon would burn next, and then heavier elements after carbon, but only if the star is massive enough to raise the temperature and density to the high levels required for the fusion of these heavier elements. The star will remain a red giant and basically just hang around in the upper right area of the H-R diagram until it finishes all of its fusion stages. Different mass stars tend to be arranged with the higher mass stars further up on the H-R diagram, but that's not always true - the arrangement of the stars in the red giant stage isn't as nice and orderly as it was during the Main Sequence stage. It is rather difficult to precisely determine the mass of a red giant star.

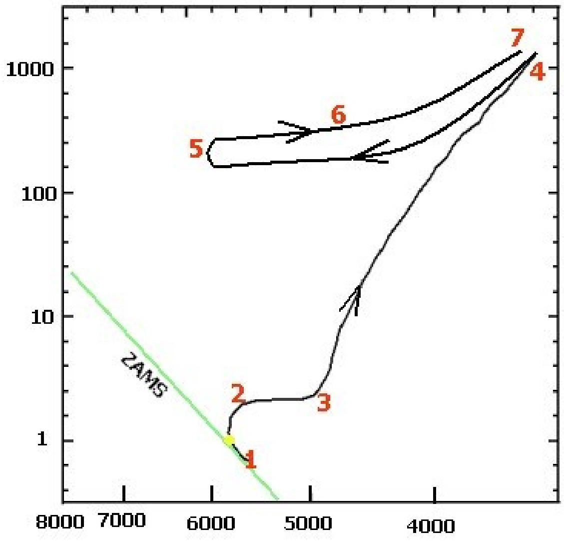


***Figure 4.*** *The various steps of the Sun's evolution are outlined here. This is also the way that most other low mass stars similar in mass to the Sun will evolve. The current location of the Sun is indicated by the yellow dot along the evolutionary path. The direction of evolution is indicated by the arrows.*

Before we find out how a star like the Sun ends its existence, let's recap the fusion history of a low mass star like the Sun. The various points listed below are marked in Figure 4.

1. Hydrogen is undergoing fusion in the core, which produces helium and energy. The star is happily doing this for 90% of its life, which is the amount of time it spends on the Main Sequence. This amounts to a total MS life of about 10 billion years for the Sun.
2. Hydrogen fusion in the core ceases for the most part, with only hydrogen fusion in a thin shell still occurring. The star from this point on is a red giant. While the outer layers get puffed up, the compression in the center starts to form an electron degenerate core.
3. Hydrogen shell burning continues in a small layer around the degenerate core. The fluffy red giant is rather unstable, and the outer layers get very convective. This can bring up some of the heavy elements from the center to the surface, which

produce some rather bizarre spectra.
4. Helium Flash signals the start of helium fusion in the core.
5. Helium core fusion producing energy and the byproducts of carbon and oxygen begins. There is also a thin layer of hydrogen shell burning around the helium core, though this isn't producing as much energy as the helium fusion.
6. Helium core burning decreases as the carbon and oxygen build up so there is only helium and hydrogen burning in thin shells. This is also the time when helium shell flashes would occur, causing disruptions in the structure of the star.
7. What comes next? That depends upon mass, with higher mass stars continuing on with further stages of fusion - maybe one more fusion stage, maybe two, or maybe three. It all depends on the mass of the star - more mass, more fusion.

For a star like the Sun, after step 7, it is pretty much dead. Follow this link to see the evolutionary paths of several other stars as they evolve from the Main Sequence through their helium fusion phases. But what happens after the helium fusion? How does a star like the Sun actually die? I'll get to that in a moment, but first, a small diversion.

## Brown Dwarfs

Believe it or not, there are some stars out there that are more boring than the Sun. This would be those that have very low masses compared to the Sun. How low? Low enough so that they don't even get to do any helium fusion - these stars only have a hydrogen fusion stage and after that, they're pretty much dead. This is likely the fate of stars less than 20% of the mass of the Sun - likely those that are Main Sequence types M5 and cooler.

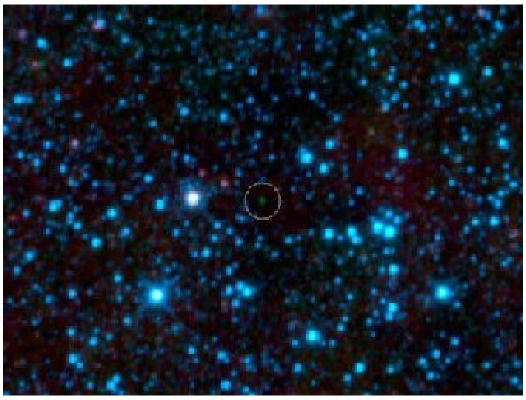


***Figure 5.*** *The coolest brown dwarf yet discovered, WISE 1828+2650, with a surface temperature of only about 300 K, (80 Fahrenheit). The colors are not true color - click on the image to see the larger view. Image credit: NASA/JPL-Caltech/UCLA.*

What's the limit for hydrogen fusion? The lowest mass that a star can have and be able to fuse hydrogen is about 8% the mass of the Sun. Remember that when stars form, the vast majority of those that form are very low mass, so there should be a lot of these very small objects out there. What do we call these really low mass not-quite-stars? These are known as **Brown Dwarfs**. These stars have surface temperatures of only about 1000 K and less, and have a fraction of the Sun's luminosity. Such objects would be very difficult to detect, and seem to have the characteristics of the L and T type stars. So are L stars really brown dwarfs? No necessarily. Some L stars are large enough to fuse hydrogen and therefore aren't brown dwarfs, while other L stars are too small to fuse hydrogen and should be viewed as brown dwarfs. It is more likely that all of the T types are brown dwarfs. It is really hard to determine which of these stars are fusing hydrogen and which aren't since they give off very little light and it is very hard to see them and accurately measure their characteristics. We have to use IR telescopes like *Spitzer* and *WISE* to detect them. In fact, the *Spitzer* has found not only brown dwarfs but also disks of dust around them - which sort of stand out since thees are quite large disks. So far the coolest (and perhaps the smallest) stars are classified as T9 types, with temperatures down to about 500-600 K.

Are there stars cooler/smaller than brown dwarfs? Of course there are. Astronomers have suggested that there be another spectral type beyond T stars, and these cool objects would be known as "Y" type brown dwarfs, or sub-brown dwarfs. Unfortunately so few Y type stars have been found that it is difficult to understand their characteristics and also to determine if they should actually be planets and not stars. Generally if they are free-floating, and not part of a binary or multiple star system, then they should be viewed as "star-like", at least in how they formed. At present the coolest such objects is also relatively close to us - WISE 0855-0714 is only 2.2 pc from the Sun. Based upon observations by the *WISE* and *Spitzer* infrared telescopes, this object has a temperature of between 225-260 K. Those are the sorts of temperatures you'd experience in Antarctica! So is it a star or a planet? At this point it may be best described as a failed star.

While it is very difficult to just find a brown dwarf, it is also very difficult to measure their masses. This was recently done, where astronomers were able to measure the masses of two brown dwarfs and found masses of only about 3% the mass of the Sun. Brown dwarfs may also play a role in the structure of our galaxy since they should be very common and could contribute substantially to the overall mass of the galaxy. For stellar evolution, Brown Dwarfs are pretty much a dead end, since they have no fusion, they don't change or evolve in any way and just cool down over time, which is pretty boring.

Since we want to see things that are more exciting than brown dwarfs, we need to return to the discussion of a star like the Sun to see what happens after it finishes all of its fusion stages.

## Stellar Death

The life stages of a star will depend mainly on one factor - its mass. How long it lives, how it will die, what it will fuse in its core - all of these depend upon the mass. Though different mass stars will evolve in slightly different ways, many will do the same sort of general things so that we can group them together. We'll first look at the case of the small stars like the Sun.

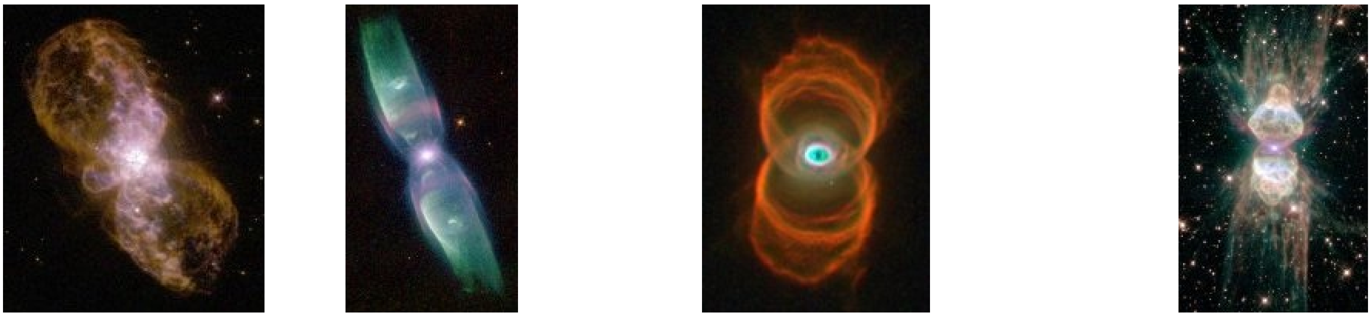
### Low Mass Death (for stars like the Sun)

Eventually the red giant phase will end when the star can no longer burn anything in its core. For the Sun, the last element it will burn is helium. Other, more massive stars will burn carbon, oxygen or neon in their cores and other heavy elements if they are massive enough. Of course, each time a star burns an element it produces heavier elements as by-products. Eventually they will have to stop burning since their cores can't get hot or dense enough for the next burning cycle to start.

When a star stops fusing an element it evolves towards the upper right corner of the H-R diagram. This is because of the compression of the core and the resulting expansion of the outer layers. The star is getting more and more puffed up. This is also a time when the convection in the outer layers is very extreme, so that the entire star is almost completely convective. If that weren't bad enough, in low mass stars like the Sun, the Helium Shell Flashes will keep occurring every once in a while and these will release a lot of energy in short bursts. This is rather like having a very nasty case of the hiccups - with the outer layers of the star actually being pushed outward. Another aspect of stars in this stage of their lives is the development of very strong stellar winds (really super winds). With the stretched out surface layers, the Helium Shell Flashes, and the super winds, there is so much going on to push the outer layers even further out. The combined energy of all these processes can help to blow off the outer layers of the star. Actually, this is not too difficult to do since the outer layers of the star are already stretched out quite a ways from the core (remember, it is a red GIANT) and so it is harder for the star to hold onto them effectively (the further from the center, the lower the gravity).

The end result is that the outer layers get blown off. As the outer layers get blown off, there will be a lot of hot gas flowing away from the star, which used to be the outer layers and there will only be the core of the star left behind. Sometimes the material will be ejected as a ring, sometimes the material gets blown off in two directions (remember **bipolar outflow**); it is also possible that the material will be blown out in bubbles. The animations provided are based upon various theories of how material is ejected. In the case of the bipolar outflow, it is believed that the interactions of two stars cause the funnel shaped outflow. In any event a large amount of material (basically all of the stuff outside of the core) gets blown out into space. This produces a structure known as a **Planetary Nebula** - and in the great tradition of naming things in astronomy, it has nothing to do with planets! It's just that in the old days when people looked at these things with telescopes, they saw that most Planetary Nebulae had disk shapes, and the only other things visible with such shapes were planets. Yes, that's a pretty lame reason, but we're stuck with it.

It's time to get back to killing off stars. During the rather nasty Planetary Nebula stage, stars like the Sun will lose about 40% or more of their mass. More massive stars will lose an even greater fraction of their mass. Some Planetary Nebulae are not nice and perfectly spherical - some have rather unusual shapes, possibly due to irregular mass loss or several different phases of mass loss. Typically Planetary Nebulae are a few light-years in size and the gas is still moving away from the star at relatively high velocities (a few thousand km/s). The gas in a Planetary Nebula will stay rather hot due to the heat from the hot, dense core, so they are visible for many years after the start of this phase.



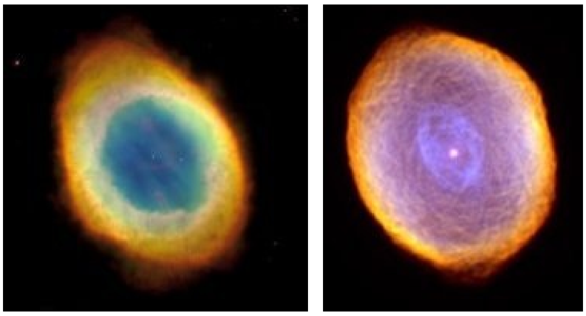


***Figure 6.*** *Examples of Planetary Nebulae. All images are from the Hubble Space Telescope. The top row shows the common bipolar outflow shaped nebulae, where material is ejected in two directions (assumed to be out the poles). The different shapes may be due to how the nebulae are tilted toward or away from us, or how well aligned the ejected material is. The two images at left are of the circular variety of the planetary nebulae. Initially it was thought that these circular shapes were due to a circular or spherical ejection of material, though some now think that the circular shape could be due to a end-on alignment of the bipolar types. Image credits: NASA, ESA, The Hubble Heritage Team (STScI/AURA), Bruce Balick (University of Washington), Vincent Icke (Leiden University, The Netherlands), Garrelt Mellema (Stockholm University), R. Sahai & J. Trauger (JPL).*

Over time the ouflow of gas from the star will stop and the gas in the Planetary Nebula will cool down and get lost amongst the rest of the gas floating around in space. A nifty thing about this material is that it is often enriched with heavy elements - remember, this phase comes after a star has finished doing all of those various fusion processes, so that there is an excess of heavy elements in the material. This is one way that heavy elements (stuff other than hydrogen and helium) can get deposited into space. This is an important point that we'll bring up again later.

All that is left of the star after the Planetary Nebula stage is the hot little core. What is the core doing? It isn't burning, but it still has to deal with the influence of gravity, which will compress the core down to the point where the material is again electron degenerate. Once it gets to that point, the compression will stop. The star is now a hot, dense but stable object. That's pretty boring, but also pretty bizarre in a way - it's still electron degenerate, which makes it rather abnormal.

The core that is left over will have a mass that is about 1/2 the mass of the Sun, but it will have a radius comparable to the that of the Earth (around 6000 km). The surface temperature will be up to 100,000 K, but it will cool off in time. The density of this object is about 1 million grams per cubic cm. This is about the same as the density of a Volkswagen - not a regular Volkswagen, but one that has been crushed down to the size of a sugar cube. Pretty dense, eh?

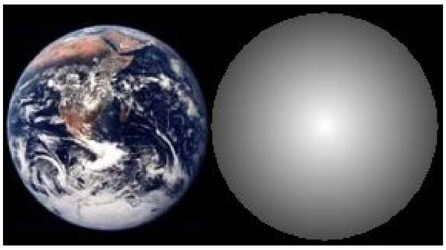


***Figure 7.*** *A typical white dwarf (right) compared to the Earth (left). Even though it has a radius similar to the Earth, the mass of a white dwarf is much closer to that of the Sun. This makes it a very dense object. Earth image courtesy of NASA.*

What do we call this hot, dense, small sized object? A **White Dwarf** - actually, this name kind of makes sense; it's small and it's hot - wow, a name of something in astronomy that actually makes sense.

Now there is a really nifty thing about white dwarfs. They are electron degenerate objects, so they don't obey the same laws of physics that normal stuff does. Someone noted a rather interesting consequence of this feature. A young student who was thinking about these things, Subrahmanya Chandrasekhar, came to a rather startling realization - that if you added more mass to a white dwarf, it got smaller in size (radius). More mass, more shrinking - this doesn't make sense, but this is the way degenerate material acts. Chandrasekhar eventually figured out that if you added enough mass, the white dwarf would be shrunk to a size of 0! Which means it could not exist - you can't have things that have no size, after all (later we'll sort of break this rule). Chandrasekhar determined that if an object is electron degenerate it cannot have a mass greater than 1.4 solar masses; any bigger than this and it would shrink out of existence - it just could not hold itself up anymore. All of the white dwarfs that we know of are stable, so they must all be less than 1.4 solar masses. Actually, where we can measure their masses, we always find that they are less than 1.4 solar masses. This mass limit is known as the **Chandrasekhar Limit**. Perhaps the best way of thinking of the Chandrasekhar limit is just like a wrestler trying to get under their weight limit, however in the case of the wrestler, he would still exist if he were overweight, unlike the white dwarf.

For a star to eventually end up being a white dwarf, it must get below the Chandrasekhar limit (1.4 solar masses). Some astronomers think that stars that started out their Main Sequence lives with about 8 times the Sun's mass can end up as white dwarfs. For this to happen, they must lose at least 6.6 solar masses on the way to being a white dwarf - that's sure a lot of material, and it can lose a large amount of that material in the Planetary Nebula stage, though it can also lose it in other ways, such as with a steady, strong stellar wind. Regardless of how it does it, it still has to do it! If it doesn't, the star won't end up as a white dwarf, but something else will happen (as you'll see later).

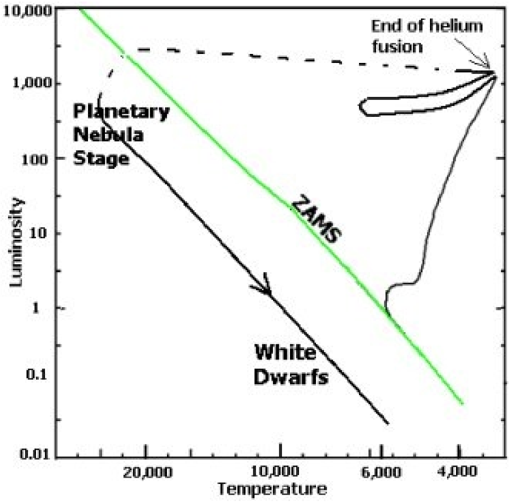


***Figure 8.*** *The entire evolution of a star like the sun, from the Main Sequence, through helium fusion and the planetary nebula stage, down to the white dwarf and ultimately black dwarf stage. The line from the end of the helium fusion stage to the planetary nebula stage is not drawn in since this path is not well known.*

In Figure 8, the evolution of the Sun is diagrammed from the ZAMS all the way to the white dwarf stage. You may notice that there is no solid line between the end of the helium fusion stage and the Planetary Nebula stage since this part of the star's evolution is kind of difficult to plot. At the start of this span, the star is a very cool red giant with a hot, compressed core. Then, when the Planetary Nebula stage starts, it basically starts to peel off the cool outer layers, revealing the hot core. In a way it sort of jumps from the far right side of the H-R diagram all the way to the left side in a very short time.

When the Sun eventually goes through the Planetary Nebula stage, it should lose about 0.4 solar masses and end up as a 0.6 solar mass white dwarf. That's not very exciting, but what else can it do? - nothing. About the only thing that a white dwarf can do is cool down. Eventually it will get cooler and less bright (remember how luminosity depends on temperature) until it gets too cool to see. Once a white dwarf completely cools down, it will become a **black dwarf**. However, that takes such a long, long time that there are no black dwarfs currently in the Universe (the Universe isn't old enough for any to exist). A rather nifty animation showing the size of a white dwarf and its ultimate fate can be seen here.

What about stars more massive than the Sun? More mass means more gravity, more gravity means more heat in the core, and more heat in the core means more fusion cycles can occur. These stars have the chance to start burning other elements, like carbon or oxygen. The more mass a star has, the more fusion cycles it can go through. Remember, it does this very quickly - big stars use up their fuel rapidly. Even though they have more fuel, they are not very economical in its usage. Even though they can burn more stuff then the Sun, they are still not very careful in how they use it. Big stars will eventually end up as white dwarfs but they tend to go through a few more burning cycles. On the H-R diagram, when these stars are burning other elements, they would just sort of wander around the area that red giants or red supergiants are found in. They'll stay as red giants or supergiants so long as the fuels lasts, but when it does run out, they'll end up down in the white dwarf location (after going through a Planetary Nebula stage), just like the Sun.

Not all white dwarfs are the same - they can have very different compositions. Remember, a white dwarf is the remains of the core, so whatever the core of the star is made of ends up being what the white dwarf is made up of. For a very low mass star, it will only go through the hydrogen fusion cycle where it produces helium. That star's white dwarf should be made mainly of helium. A star like the Sun will burn helium, producing carbon and oxygen. The Sun's white dwarf will be made mainly of carbon and oxygen. There are white dwarfs out there made of various things like mixes of oxygen, neon and magnesium, to name a few. The larger the star was on the main sequence, the heavier the final fusion product will be - and this will determine the final composition of the white dwarf. Now let's look at an interesting fate for some white dwarfs.

## Nova

If a white dwarf is sitting all by itself in space like the Sun's white dwarf will be, not much else will happen with it. If it is a binary system, especially a close binary system where things are really tight, it can get very interesting indeed.

It is possible for mass to transfer from one star to another in a close binary system. This can happen in certain stages of the binary star system's evolution. One example of what can happen is the following - let's say you have two stars of slightly different mass. The more massive star will die first (remember, mass determines fate and big mass means short life), the big star will go through its various stages of evolution and end up as a white dwarf before the less massive star has a chance to even do much of anything. In fact, the lower mass star will still be on the Main Sequence long after the other star goes through its entire life. You now have a white dwarf star and a Main Sequence star. Eventually the remaining MS star will start to die and will enter the Red Giant stage - nothing unusual about that. As it puffs up it will get larger and larger and will fill up a gravitational boundary, the **Roche Lobe**, around the binary system.

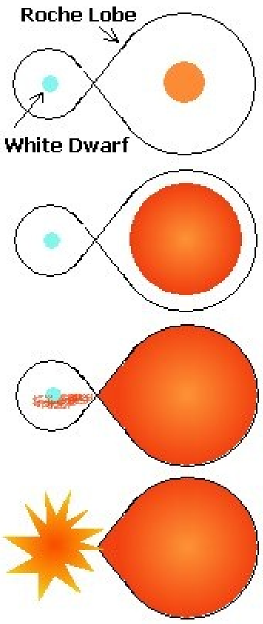


***Figure 9.*** *The ingredients needed for a nova. Two stars, one a white dwarf, the other a star becoming a red giant, are in orbit about one another. The Roche Lobe marks the gravitational limit for each star. As the red giant expands, the material in its outer layers don't expand out in any direction due to the proximity of the nearby white dwarf, so the material is funneled toward it. This is due to the constraints of the Roche Lobes. Eventually the material on the white dwarf will ignite as a nova.*

The Roche Lobe isn't a physical barrier like a wall, but it just defines how the gravitational pull of the binary system causes material to move in certain ways. As the red giant fills up its side of the Roche Lobe, the material will not just expand outwards, but will instead be funneled towards the other star - that's all due to our electron degenerate friend's high gravity. Now the material from the red giant is being transferred over to the other star in the system, which in this case is a white dwarf. This cannot be good! The material transferring from the red giant will not just dump directly onto the white dwarf since the whole system is moving and things are going around in orbits, so the material sort of spirals in. It will gradually build up a disk around the white dwarf. The material builds up around the white dwarf into what is called an **accretion disk**. The white dwarf is rather hot and the material gets heated up in the process of spiraling in, so it will tend to give off ultraviolet (UV) radiation. This is good, since it provides a way for astronomers to identify such binary systems. Remember, this is in a binary system and the only thing that might be visible in a regular telescope is the red giant, which is too cool to produce any large quantities of UV radiation. The presence of the large amounts of UV radiation points to an unseen accretion disk with a white dwarf buried inside it. Gradually material will get to the white dwarf and build up on its surface. What type of material is it? It is what the outer layers of stars are made up of, which is the regular mix of mainly hydrogen with some helium in it.

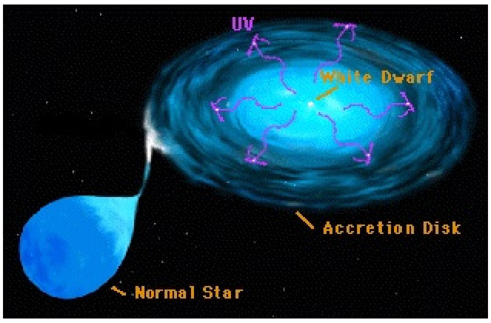


***Figure 10.*** *The set up for a nova - one star getting material ripped off, another star (white dwarf) pulling the material in. The material forms an accretion disk which will heat up to the point where it gives off UV light.*

Now we have a white dwarf getting dumped on. After some time (years, or perhaps even decades), the material that accumulates on the surface of the white dwarf will ignite in an explosive blast. This explosion has a brightness about 100,000 times greater than the Sun's luminosity. What you have here is a Nova. Novae (that's the plural form) will stay bright for weeks, but are not as bright as supernovae (which we'll get to later). While the explosion is pretty powerful, energetic and bright, it doesn't destroy the stars involved. The nova is produced by mass being transferred in a binary system, so it is possible for it to happen again and again in the same star system. This is known as a **recurrent novae**. There are 10 known recurrent novae in our galaxy. The current record holder for most frequent eruptions is U Scorpii (in the constellation of Scorpius). This system went nova in 1863, 1906, 1917, 1936, 1945, 1969, 1979, 1987, 1999 and 2010. Click here to see the light variation of U Scorpii during the 2010 nova. I guess a recurrent nova is sort of like a repeat offender - they just can't help themselves and keep doing the same thing over and over. In the case of U Scorpii, even though it has gone off at least 10 times, it is possible that it could go off again!

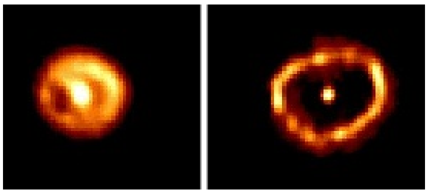


***Figure 11.*** *Nova Cygni seen at two different times, 1992 and 1993 (left and right respectively). The expansion of the blast shell over time is obvious in the two images. The two stars that are the source of the nova appear like one star in the middle. Image credit: F. Paresce, R. Jedrzejewski (STScI) NASA/ESA.*

Novae are so bright that they can at times be seen in other galaxies millions of light-years away. Eventually the explosion will fade away, though it did cause a nice light show while it lasted. There can be dozens or hundreds of novae occurring in a galaxy each year, since there are so many white dwarfs out there. A system that produces a nova will not be able to repeat the process forever, since eventually the red giant will become a white dwarf, so you'll end up having a system containing two white dwarfs. What will these white dwarfs do? - nothing but cool off slowly, eventually becoming a pair of black dwarfs, but that takes a very long time. They end up being pretty dull and boring in the end.

The Sun will not become a nova (remember, it takes two stars to have a nova), so it will have a pretty boring end. Sorry, folks, this is pretty much the end of the line for low mass stars like the Sun.

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**Now that you've read this section, you should be able to answer these questions....**

- How does the interior of the Sun change over time? What effect does this have on the rest of the Sun?
- What happens when the hydrogen runs out?
- What happens to the planets when the Sun goes through its Red Giant phase?
- What are the characteristics of a Red Giant?
- What causes helium fusion to start?
- What happens once helium fusion ceases?
- What happens during the Planetary Nebula stage?
- What are the characteristics of a White Dwarf?
- What is the Chandrasekhar limit?
- How can the evolution of a star like the Sun be depicted on an H-R Diagram?
- What is needed to produce a nova?