Stellar Evolution

We see the process of birth, aging, and death at work in everything living. However, until recently, we viewed this drama as unfolding against an unchanging backdrop. The stars were seen as an immutable constant. Now we know that they, too – in a very real sense – are mere mortals. Within our galaxy, stars are constantly born, live out their lifetimes, and die.

Our galaxy and others are collections of stars of all ages. The birth and death of stars is an ongoing process. Stars are formed by the gravitational collapse of interstellar gas and dust.

The Birth of a Star

When the first stars and galaxies formed some 13 or so billion years ago, not all of the available primordial hydrogen and helium was used up in the process of star formation. In galaxies such as ours, vast clouds of gas remained in the galaxy disk as interstellar matter. The first-generation stars evolved producing in their cores nuclei of elements heavier than helium. Following these stars' explosive deaths, these elements, along with even more massive nuclei produced in the explosions themselves, were blasted into interstellar space, enriching the primordial hydrogen and helium with heavier elements. This enriched interstellar material is the raw material from which later generations of stars have formed.

Stars are simply hot, dense concentrations of interstellar matter. In general, clouds of interstellar matter do not change much in size. They are in hydrostatic equilibrium, meaning that their tendency to contract due to gravity is balanced by their tendency to expand due to temperature and turbulence. Star formation begins when this balance is disrupted and gravity gets the upper hand. Observational and theoretical considerations suggest several different mechanisms that might cause this.

Interstellar Matter

- Chemical nature: mostly hydrogen, most of the rest is helium, and some heavier elements.
- Physical nature: mostly gas, some solid particles.
- Origin: hydrogen and helium from the Big Bang, the heavier elements were produced in the cores of massive stars and ejected into interstellar space by supernova explosions.

The gravitational collapse of a cloud of gas and dust has two important consequences. First, while the cloud is still large, its rotational motion is not obvious. However, as the cloud collapses, it spins faster and faster, much as ice skaters spin faster and faster when they pull in their arms. The physical explanation for this is conservation of angular momentum. As the rotating mass becomes more and more compressed, its rotation speed increases, keeping the angular momentum constant. The rapid rotation has very important consequences for the formation of planets, which we will discuss in a later reading on our solar system.

A second consequence of gravitational collapse is that the particles of the cloud speed up and collide more frequently as they fall inward. Temperature is simply a measure of the average kinetic energy (energy of motion) of the particles, so the collapse produces an increase in temperature. This effect is greatest at the center of the cloud. As the density of the central region increases, particles collide more often and pressure builds up. Eventually the density increases enough to trap electromagnetic radiation. This dramatically slows the collapse of the central region. Meanwhile, material from the rest of the cloud continues to fall toward the center, increasing still further its temperature, density, and pressure.

The central region is now a protostar. Although, as the name implies, a protostar is not quite a star, it has many star-like properties. It has a visible surface with a temperature of several thousand kelvins. If you could see this object, it would look like a large red star. Because of the high internal temperature of the protostar, the atoms collide violently enough to knock the electrons out of their orbits, producing a state of ionized matter known as plasma.

As the protostar continues to contract gravitationally, the core temperature continues to increase. When the internal temperature becomes high enough to initiate thermonuclear reactions converting hydrogen into helium, the protostar becomes a star.

Hubble photo of the star forming region in the Eagle Nebula

Hydrogen Fusion

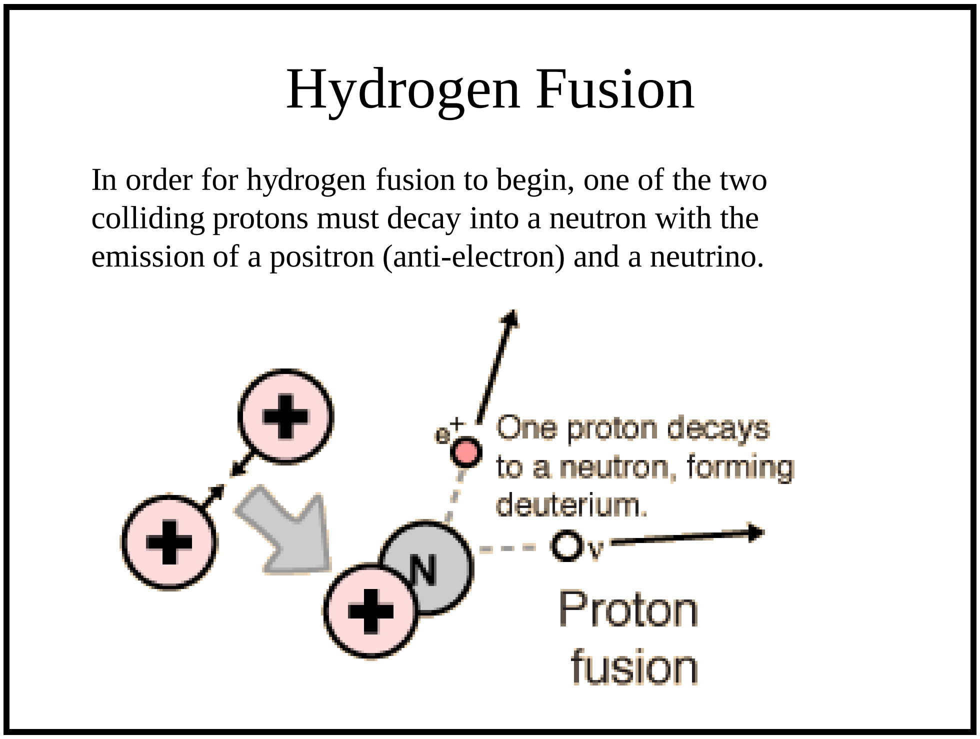
In many prehistoric and ancient cultures, the sun was thought to be a supernatural phenomenon, usually personified as a god. It was an ancient Greek thinker who, as far as we know, was the first to offer a natural explanation for the sun. Anaxagoras proposed that the sun was a giant flaming ball of stone rather than the chariot of the god Helios. Prior to the nineteenth century, speculation about the source of the energy the sun radiated centered on combustion due to the similarity between the sun and fire.

By the nineteenth century, the concept of conservation of energy was beginning to be understood and it was realized that if all of the sun's mass were in the form of some combustible material such as coal, it would burn out in less than 10,000 years – which it clearly had not done. Combustion, or any other chemical reaction, therefore cannot be the sun's energy source. In the mid-1800s, steady gravitational contraction was suggested as an alternative explanation. However, this source would extend the sun's life to only a few million years, and soon it was clear that even this explanation didn't provide an age that was long enough.

The early part of the twentieth century saw the beginning of our understanding of nuclear physics. Nuclear reactions often release relatively large quantities of energy, millions of times that released in chemical reactions. It was natural, therefore, to suspect that nuclear reactions might be involved in the production of stellar energy. In

1928, a specific nuclear reaction was suggested: the conversion of hydrogen nuclei into helium.

In order for a nuclear reaction to occur, nuclei must come close enough to one another for the strong nuclear force to pull them together. They must almost bump into one another. However, the protons (hydrogen nuclei) that initiate the fusion reaction repel each other due to their positive charge (the electromagnetic force). To overcome this repulsion sufficiently to allow protons to touch, they must be moving very fast, i.e. the temperature must be very high. The minimum temperature for any significant fraction of the protons to bump into one another is 10 million K. If the protostar has sufficient mass to develop this temperature in its core, a star is born. From this point until it exhausts its core of hydrogen, the star is called a main-sequence star. Our sun is a main-sequence star.



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If two protons collide, the strong nuclear force will bind them together temporarily. However, the very strong repulsive force that the two positive charges in such close proximity exert on each other is sufficient to break the bond that the strong nuclear force has established between them, bringing the fusion reaction to a halt. The only thing that can prevent this occurrence is for one of the protons to be transformed into a neutron by a beta-positive nuclear reaction. This is an extremely unlikely reaction in light of the small fraction of a second for which the two protons are in contact. Such improbability is good, however, for a star's life expectancy, because it allows stars to slowly consume

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their hydrogen fuel. Otherwise, our sun would not have been the constant source of life-sustaining energy that it has been for the last 4.6 billion years.

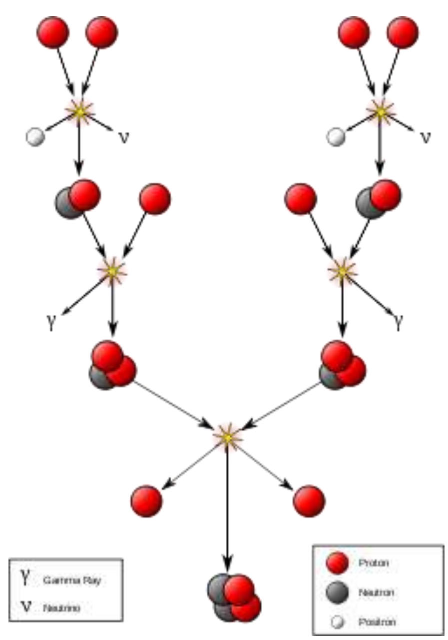
If the beta-positive reaction does occur, the resulting nucleus contains one proton and one neutron. This is a form of hydrogen known as deuterium, or heavy hydrogen. After the bottleneck of the beta decay has passed, the remainder of the reaction goes quickly. First another proton is added, making helium with two protons and one neutron, known as helium-3 (for the three nucleons in the nucleus). The final step in the hydrogen fusion chain is when two helium-3 nuclei combine to form helium-4 (two protons and two neutrons), releasing two protons in the process. Overall, four protons have ceased to exist, and in their place are a helium-4 nucleus, two positrons, two neutrinos, and energy. Using nuclear notation, this reaction is written as:

$$4({}^{1}_{1}\mathrm{H}) \rightarrow {}^{4}_{2}\mathrm{He} + 2({}^{0}_{+1}\mathrm{e}) + 2({}^{0}_{0}\nu) + \text{energy}$$

The positrons are represented by the symbol 'e' with the zero superscript indicating that it is not a nuclear particle and the +1 subscript indicating a positive charge as opposed to the negative charge on an electron (also represented by the symbol 'e'). The neutrinos are represented by the symbol 'ν', the Greek letter *nu*, with the zeros representing a non-nuclear particle with no charge. The energy comes from the decrease in mass associated with the reaction according to Einstein's equation $E = mc^2$.

Hydrogen Fusion

The net effect of the hydrogen fusion reaction is the conversion of four protons into a helium nucleus, two positrons, and two neutrinos. Because four protons have slightly more mass than the helium, the positrons, and neutrinos, some mass is converted into energy, which then works its way to the surface of the star and is radiated away.



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The mass of a main-sequence star determines its properties. These are usually expressed in units based on the value of the property for our sun. The subscript 'o' stands for our sun. Thus, if a star emits 25 times more energy per second than our sun, its luminosity is expressed as $L = 25\ L_o$.

Star properties

- Size - 300 R_o to 0.01 R_o.
- Luminosity - 1,000,000 L_o to 0.0001 L_o.
- Surface temperature - 40,000 K to 3000 K.
- Core temperature - 20 to 10 million K.
- Age - 0 to ~13 billion years.
- Chemical composition - mostly H and He with varying amounts of heavier elements depending mostly on age.

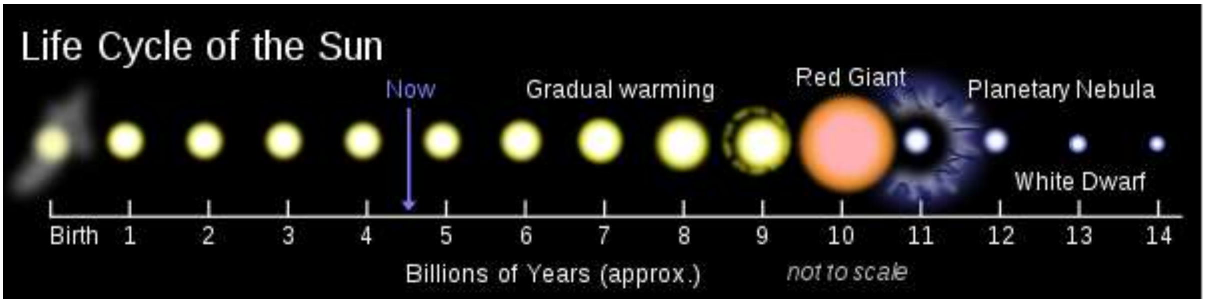
The Evolution of Low-Mass Stars

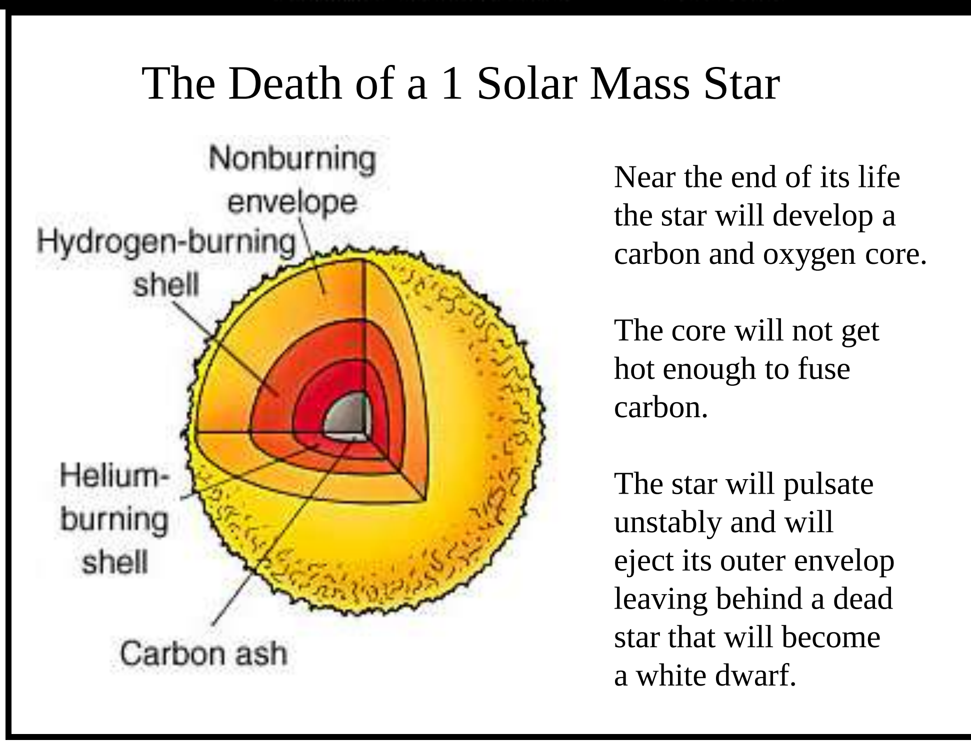
Mass is the single most important property in determining how a star evolves, and particularly how it dies. With respect to their deaths, stars can be divided into three distinct mass categories: very low mass (0.08 to 0.4 solar masses), low mass (0.4 to 9.0 solar masses), and high mass (9.0 to 60 solar masses). The physics of the deaths of very-low-mass stars is complicated. It is also hypothetical in the sense that their lifetimes exceed the age of the universe. Because none have ever died, we will not discuss them further in these readings.

For low-mass stars such as our sun, as the hydrogen in the core is depleted, the surface temperature and luminosity slowly change. Even though the hydrogen is being depleted, the energy produced by hydrogen fusion increases, exerting greater outward pressure, causing the outer regions of the star to expand and cool. They eventually become red giants with cores completely depleted of hydrogen, the luminosity being provided by hydrogen fusion in a shell surrounding an inert helium core.

Because energy is not being generated in the core, gravity contracts the core, causing the core temperature to increase. Eventually the core temperature becomes sufficient to fuse helium into carbon and some oxygen. Higher temperatures are required than is the case for hydrogen fusion because the helium nuclei have two protons and thus repel each other more strongly than do hydrogen nuclei.

When the helium is depleted, the core will again contract and heat up, but it will not reach sufficient temperatures to fuse carbon. Low-mass stars die with carbon and oxygen cores. In the dying process, the star will begin to pulsate, and eventually the outer region will be ejected, leaving the small hot central region behind. This dead star is now known as a white dwarf.





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The Ring Nebula - when a star like our sun dies it ejects its outer regions. A dead white dwarf star is left behind.

The Evolution of a High-Mass Star

The dividing line between low-mass and high-mass stars is based on whether or not their cores reach temperatures sufficient to fuse carbon. The mass at which this occurs is not known exactly, but it is generally thought to be about nine solar masses. Once carbon fusion begins, the star will go through a sequence of fuels, contracting, heating, and fusing the next heaviest element left in the core. The star thus becomes layered, like an onion.

The succession of fusions continues until the star develops an iron core. Up to this point, each successive fusion reaction has resulted in the liberation of energy. That is, in each reaction, the products of the reaction have slightly less mass than the nuclei initiating the reaction, and an amount of energy given by $E = mc^2$, where m is the mass lost, is released. This helps to support the star against gravity. However, iron is the most stable nucleus that can be produced in a star. As a result, when the temperature becomes sufficient for the iron to react, rather than releasing energy, energy is absorbed, producing more contraction and still-higher temperatures. The result is a run-away reaction. The higher temperature causes the iron reactions to speed up, absorbing even more energy, and so on.

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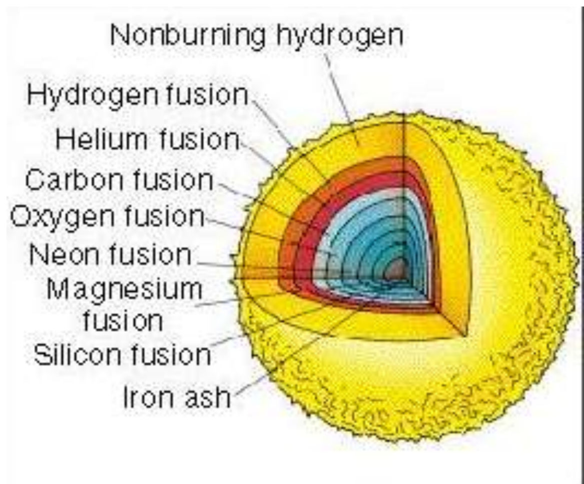
The Death of a 15 Solar Mass Star



Near the end of its life the star will develop and iron core.

Reactions in the iron core will cause the star to explode (supernova) scattering its contents into interstellar space. A dead neutron star will be left behind.

Elements heavier than iron will be created in the explosion.

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The core temperature becomes so high that the nuclei themselves are broken down into individual protons and neutrons absorbing still more energy. At still-higher temperatures, electrons and protons combine to produce neutrons and neutrinos; again, an energy-absorbing reaction. Because the number of protons and electrons is exactly the same (the core is electrically neutral), the core now consists entirely of neutrons with the neutrinos being radiated away from the core. In a fraction of a second, the earth-sized iron core is transformed into a neutron core about 10 miles across.

The unsupported outer regions are now free-falling toward the neutron core. The implosion is converted into an explosion by a combination of events. The infalling material will hit the surface of the incompressible neutron core with speeds approaching the speed of light. Because the core is incompressible, the infalling material will bounce back at these same speeds. In addition, the pressure of the neutrinos leaving the core, and the energy generated by fusion in the infalling material, add energy to the explosion. The resulting powerful explosion is called a supernova. The energy of the explosion produces elements more massive than iron, all the way up to uranium and beyond. The supernova blasts this debris into interstellar space, enriching the interstellar material with heavier elements.

The supernova may leave behind the neutron core, in which case it becomes a neutron star. If the initial value of the star's mass is high enough (we do not currently know the value of the mass required) the neutron core will be more massive than

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neutron pressure can support, and the result will be complete gravitational collapse. This state of matter is known as a black hole.

The Crab Nubula - the explosive death of a high-mass star; a supernova.

The Crab supernova was observed on earth in 1054. Today it is a rapidly expanding cloud of gas and dust with a pulsar (a rapidly rotating neutron star) at its center.

The material in the cloud is rich in elements heavier than helium.

In 1967, Jocelyn Bell, then a graduate student, observed strong radio pulses coming from space. Initially she and her thesis advisor, Anthony Hewish, were baffled by the seemingly unnatural regularity of the emissions. Although they never took it too seriously, they dubbed the discovery LGM-1, for "little green men" (a common name at the time for intelligent beings of extraterrestrial origin). Soon other LGMs were discovered, and the name was changed to *pulsars* (a contraction of the words "pulsating" and "star"). In 1968, Thomas Gold suggested that pulsars are rapidly rotating neutron stars emitting radiation from their magnetic poles. Because the axis of rotation differs from the axis of the magnetic field, pulsars act like a lighthouse, producing a pulse of radiation when the beam rotates past the earth. The frequency of these pulses is determined by the rotational period of the neutron star. Pulsar periods range from milliseconds to several seconds.

In our story of the universe from the Big Bang to the present day, the most significant result of stellar evolution is that the life and death of high-mass stars is the only way in which elements more massive than helium can be produced in the universe – elements such as carbon, oxygen and all the other familiar elements that make up our planet and our bodies. When Carl Sagan said, "We are stardust," he was speaking quite literally.

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