Nuclear Fusion and the Lives and Deaths of Stars

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It's all about mass

When the core temperature of a collapsing protostar is greater than a few million degrees, the core crosses an important threshold. At these high temperatures, the positively charged nuclei of hydrogen (one proton) and helium atoms (two protons, two neutrons) can no longer hold on to their electrons. Instead, the electrons have so much energy that they escape from their atomic orbits. What remains are hydrogen nuclei (each a free proton with a positive charge of +1) and free helium nuclei (each with a positive charge of +2) zipping around in a dense cloud of free electrons (each with a negative charge of -1).

At temperatures of ten million degrees K of higher,[1] the hydrogen nuclei are moving at such high speeds that they can smash into each other. These collisions release heat, in a process called *nuclear fusion*, which creates outward pressure which pushes back against gravity and slows or stops the further gravitational collapse of the protostar.

The Proton-Proton Chain and Nuclear fusion

In 1926, English astrophysicist Arthur Eddington proposed a method for energy generation in stars based on Albert Einstein's theory of special relativity. Einstein had put forward the theory of special relativity in 1905. The most widely known part of that theory is his equation

$$E = mc^2.$$

Mathematically, this equation tells us that energy (E) is equivalent to mass (m) and that the amount of energy contained by a piece of mass is found by multiplying the mass by the square of the speed of light (c^2). Effectively, $E = mc^2$ expresses two important ideas: 1) that mass is simply one way in which the universe stores energy, and 2) that energy can be taken out of this storage device if the physical conditions (temperature, density,

[1] On temperatures: Scientists usually use the Kelvin temperature scale. Use the following formulae to convert from one scale to another: ºF = K × 9/5 – 459.67 (Kelvins to degrees Fahrenheit) and ºC = K – 273 (Kelvins to degrees Celsius). Note that the freezing point of water is 32 ºF = 0 ºC = 273.15 K, the boiling point of water is 212 ºF = 100 ºC = 373.15 K, and absolute zero is -459.67 ºF = -273 ºC = 0 K. Temperatures at the surface of the Earth are about 80 ºF ~ 27 ºC ~ 300 K, at the surface of the Sun about 10,000 ºF ~ 5,500 ºC ~ 5,800 K, and in the core of the Sun about ~ 18,000,000 ºF ~ 10,000,000 ºC ~ 10,000,000 K.

pressure) are right. The right physical conditions for this to happen exist deep inside stars, but nowhere else.[2]

Eddington suggested that four hydrogen nuclei (i.e., four individual protons) could be combined, or fused together, to make one helium nucleus in a process called *nuclear fusion*. In 1926, physicists knew that the mass of one helium nucleus is slightly less than the sum of the masses of four protons, and so Eddington suggested that the 'lost' mass was somehow converted to energy and that this energy could power stars. He had no idea how this might happen.

In 1929, Cecilia Payne-Gaposhkin, in the work she did to complete her Ph.D. dissertation at Harvard, was able to calculate the abundances of the elements in the atmosphere of the Sun and concluded that most of the Sun, and almost certainly also most of the matter in all stars, is composed of hydrogen. For the first time, astronomers knew what stars were made of. Stars had nearly inexhaustible supplies of hydrogen and so, according to the process sketched out by Eddington, could power themselves for extremely long lengths of time. Aided by the discovery of the neutron in 1932 by English physicist James Chadwick, the subsequent recognition that the nucleus of helium atom must have two protons and two neutrons, and the development of the theory of quantum mechanics in the 1920s and 1930s, German-American physicist Hans Bethe, working at Cornell University in 1938, deduced the sequence of nuclear reactions that take place in the cores of stars that fuse hydrogen nuclei into helium nuclei.

The energy available through nuclear fusion

In a sequence of reactions called the proton-proton chain, four protons (^{1}H) combine to form a single helium nucleus (^{4}He) made of two protons and two neutrons; however, this does not occur via the highly improbable simultaneous collision of four particles. Instead, the proton-proton chain involves six, not just four, protons and several intermediate steps.

First, two protons collide. After the collision, one of the protons is converted into a neutron through the emission of two particles, a positron (the anti-particle partner of an electron, having the mass of an electron but a positive charge) and a neutrino (a very low mass particle with no electric charge). The resulting particle contains both a single proton, and so it is still a hydrogen nucleus, and also a neutron, so it is the nucleus of a heavier than normal hydrogen atom known as deuterium (this heavy hydrogen atom is denoted as either ^{2}H or D; the nucleus is a deuteron).

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[2] One active area of scientific research is aimed at generating the physical conditions for these collisions to occur in laboratories on Earth, in devices called tokamaks. See, e.g., https://www.iaea.org/topics/fusion.

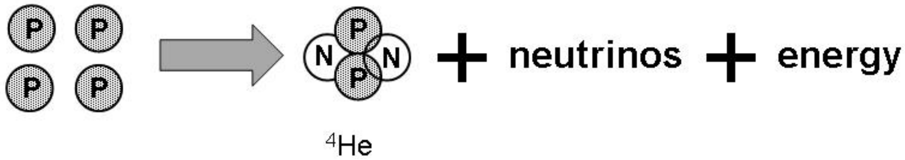

Figure 1: In the proton-proton chain, four protons (each the same as hydrogen nucleus) combine to form a helium nucleus. In the process, some mass is converted to energy, and a little bit of mass is converted into particles called neutrinos. This nuclear fusion reaction generates the energy that powers the Sun.

The positron will quickly find its anti-particle, an electron; in that collision, they will *annihilate*. When this happens, all the mass turns into energy in the form of a very high energy gamma ray photon. The gamma ray cannot travel far before bumping into a particle (a proton or an electron or a helium nucleus). Immediately, that particle absorbs the photon, which gives that particle more energy and thereby makes it move faster. Since the distribution of speeds of particles in a gas determines the temperature, when repeated many times this first step in the proton-proton chain has the effect of heating up the gas at the center of the star.

The neutrino has properties such that it only rarely collides with other particles (it is known as a weakly-interacting particle), so almost all the neutrinos produced in this reaction fly right out of the Sun.[3]

In the next step in the proton-proton chain, the deuterium nucleus collides with another proton to form a lightweight helium nucleus, with two protons but only one neutron (^{3}He; called helium-three). This reaction also generates a gamma ray, which will be absorbed by a nearby particle, giving that particle excess kinetic energy and further heating up the surrounding gas.

These first two reactions must each happen twice so that two ^{3}He nuclei are created. Finally, these two ^{3}He nuclei collide, forming a ^{4}He nucleus and knocking loose two protons. The combined mass of four protons is 6.690×10^{-24} g while the mass of one ^{4}He nucleus is only 6.643×10^{-24} g. The fractional difference in mass between the input and output particles, equal to 0.7 percent of the starting mass, is the amount of mass converted to energy in this process. If the entire mass of the Sun were available (which it is not) for this mass-to-energy conversion process, the proton-proton cycle could power the Sun for 100 billion years. In fact, only the hydrogen in the Sun that is hotter than 10^7 K can undergo fusion, and this hydrogen is in the central part of the Sun called the core.

[3] https://neutrinos.fnal.gov/sources/solar-neutrinos/

Since the core contains about 10% of the mass of the Sun, the Sun could power itself for about 10 billion years.

Requirements for the Proton-Proton Chain

The collisions that power the proton-proton chain involve positively charged nuclei colliding with other positively charged nuclei. Just like the north poles of two magnets, positively charged particles repel, however, so two protons are unlikely to collide except under the most extreme conditions. In fact, if two protons were propelled toward each other at low speeds, the repulsion they exert on each by virtue of their positive charges would prevent the collision from happening, just as two automobile drivers driving toward each other on a single lane country road at low speeds would likely see each other in time to avoid the collision, either by slamming on their brakes or veering out of each other's way.

Let's follow the potential car crash analogy further. We can ask, under what conditions would the two drivers be unable to avoid a collision, either with each other or with an identical innocent-bystander car? Two such pre-conditions would contribute to ensuring that a collision <u>will</u> occur: high speeds and a high density of cars. High speeds ensure that neither driver will have enough time to react after discovering another car in their path; high density — meaning that the parking lanes on both sides of the narrow road are packed with other cars so that there is no safe place toward which either car can turn without hitting another car — ensures that any effort to avoid a collision with a car in the driver's lane will almost certainly cause a collision with another, nearby vehicle. If both conditions — high speeds and high density — are met, a collision between the two cars is inevitable.

In order for two protons to collide, they must get close enough to touch, that is, they must come closer than one nuclear diameter (10^{-13} cm). The minimum temperature required for two protons to be moving fast enough to overcome their mutual repulsion at this close distance is 10 billion K. This implies that while the surface of the Sun has a temperature of only 6,000 K, the core must have a temperature about one million times hotter if nuclear fusion is the process that powers the Sun; yet astronomers were certain, even in the 1920s, that the core of the Sun could not be much hotter than about 10 million K, which is about 1,000 times cooler than the required 10 billion K for nuclear fusion. They reasoned, correctly, that if the core temperature of the Sun were much hotter than 10 million K, the intense pressure from the super-hot gas deep inside the Sun would cause the outer layers of the Sun to expand and make the Sun bigger than it actually is.

Clearly, if stars generate energy through nuclear fusion but do so at temperatures of tens of millions of degrees rather than billions of degrees, then this simple picture is missing an important detail about the nuclear fusion process in stars. That idea is the kinetic theory of gases. In a gas — and the particles at the core of the Sun are indeed in the form of a gas — every particle has a different speed. Some particles are moving slowly in

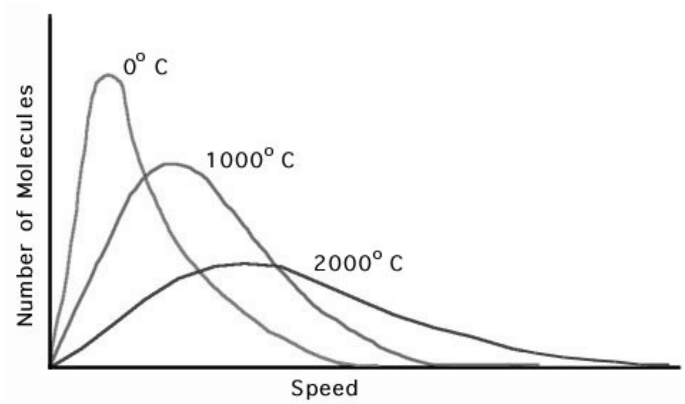

Figure 2: The Maxwell-Boltzmann distribution depicts the speed versus the number of particles in a gas moving at each speed. As the gas temperature increases, the entire distribution broadens and shifts toward higher speeds.

comparison to the average; others are moving much faster than the average. When we ask "what is the temperature of the air in this room?" we are actually asking "what is the average speed of all the oxygen and nitrogen molecules in the air?" In this distribution of velocities, known as the Maxwell-Boltzmann distribution, some particles will be moving twice as fast and others as much as six times as fast as the average; a few particles will be moving even faster, and of course some will be moving slower than the average. So if the temperature of the gas is 10 million degrees, a very small fraction of particles are moving with speeds six times faster, equivalent to speeds for the average velocity of particles in a gas at 60 million degrees. Thus, we do not need the temperature of the gas to be 10 billion K in order for a very few particles to be moving at speeds as fast as the average for a 10-billion-degree gas. Thus, the kinetic theory of gas makes nuclear fusion possible, even at the temperatures at the core of the Sun.

If we start at the core of the Sun and move radially outwards toward the surface, both the temperature and density of the gas will slowly decrease. Outside of a critical radius, the temperature and density will be too low for any nuclear fusion reactions to take place. The region inside this critical radius is the *core* of the star; the region outside the core is called the *envelope*. In the Sun, only the hydrogen located in the core can participate in the proton-proton chain; the hydrogen in the envelope is inactive in the nuclear fusion process.

The heat released from fusion reactions in the core is slowly transferred upwards, where it is radiated away from the stellar surface into space. The fusion reactions, every second, generate exactly enough pressure to balance the amount of energy lost from the surface to space and to battle gravity to a standstill. An object that can do this is a normal star. The truce, this period during which the inward pull of gravity and the outward push from heat are in equilibrium, will hold for a long time (millions to 100s of billions of years, depending on the mass of the star), but this balance is only temporary.

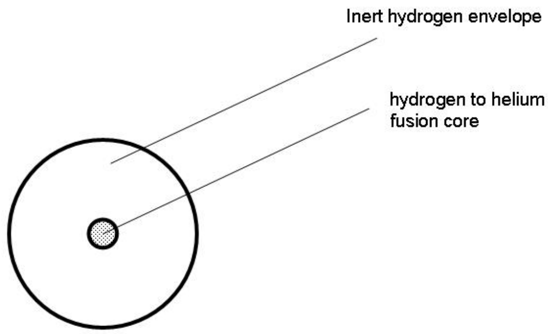

Figure 3: The internal structure of a star like the Sun. The core, in which hydrogen fuses to helium, is surrounded by an inert hydrogen envelope. The diameter of the core is about ten percent of the diameter of the star.

After the fuel in the core is exhausted, the star will continue to cool off at its surface but can no longer replace the heat lost from the surface through proton-proton chain fusion reactions in its core. Gravity, by patiently outlasting the hydrogen available for fusion in the core, wins again

Brown Dwarfs

If the mass of the collapsing protostar is below about eight percent of the mass of the Sun, its gravity is too weak for it to generate sufficient temperatures and pressures to trigger the fusion reactions that transform protons into deuterium, and so it will never become a star; however, if the protostellar mass is below this threshold but above about one percent of the mass of the Sun, the internal temperatures and pressures will become high enough (1 million K) to trigger the direct fusion of deuterium into helium (step three in the proton-proton chain). Such an object is known as a *brown dwarf*. Since stars have about one deuterium atom for every 6,000 hydrogen atoms, in comparison to stars brown dwarfs have very little fuel available that they can tap for nuclear fusion; hence, even the most massive brown dwarfs lack the fuel necessary to power deuterium fusion reactions for very long. Once brown dwarfs run out of deuterium fuel, they gradually cool off and fade away.

Red Giants

When a star runs out of hydrogen fuel in the core, gravity once again gains the upper hand, and the star again begins to contract. The contracting star now consists of two principal parts, a shrinking and inert (no active nuclear fusion reactions) helium core and an inert hydrogen envelope. What happens next is one of the weirder aspects of stellar astrophysics; the core will get smaller and, as a result, the star as a whole will expand.

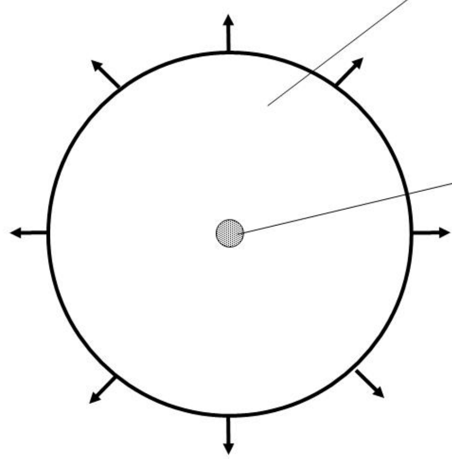

Figure 4: The internal structure of a star when it begins to die. In the core, the hydrogen fuel is exhausted and the helium is too cool for fusion. The cooling core contracts; this has the effect of heating the surrounding hydrogen envelope, which causes the outer layers of the star to expand. The star is on the way to becoming a red giant.

As gravity crushes the core into a smaller and smaller volume, the temperature of the compressed core begins to rise, from ten to 15 to 20 to 25 million K. While the helium core temperature rises due to gravitational compression, the temperature at the bottom of the hydrogen envelope also must rise because it is heated from below by the rising temperature of the shrinking core. The gentle rise in internal temperature forces a parallel rise in internal pressure. As a result, while the very innermost part of the star is squeezed, compressed, and heated by gravity, the envelope the star is pushed outwards by the rising internal pressure and becomes more rarefied.

The expanding outer layers of the star result in a star that now has a larger surface area than before. By virtue of having a larger surface area, the star can radiate away the same or even more energy at a cooler surface temperature. Consequently, dying stars grow bigger, brighter, cooler, and redder. They become *red giants*.

Stars that are born with several times the mass of the Sun have yet another trick up their sleeves. As the core temperatures of these stars rise into the tens of millions of degrees, the temperature of the hydrogen gas at the bottom of the envelope that had been just outside the core rises just above ten million degrees. Gradually, the proton-proton chain turns on in a thin shell of hydrogen gas deep inside the star but outside of the inert helium core. This extra release of energy in a layer outside of the core heats up and expands the

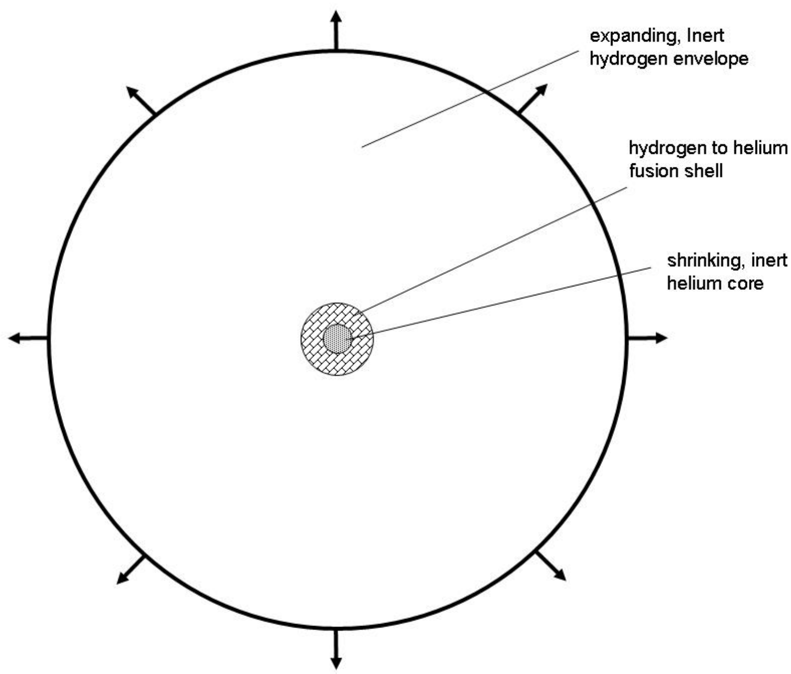

Figure 5: The internal structure of a star when it becomes a hydrogen-shell fusing red giant. In the core, the helium core continues to contract. Surrounding that core, a shell of hydrogen becomes hot enough to fuse into helium. The release of heat from those fusion reactions heats up the outer hydrogen envelope more, causing it to expand further.

envelope further, making these stars even bigger, more luminous, and cooler. These are hydrogen-shell fusing red giants. Once again, the star achieves internal pressure equilibrium, but the balance between gravity and thermal pressure that a star reaches during this red giant stage will be short-lived, as less fuel is available for fusion in this thin shell than was available in the core.

White Dwarfs

Deep inside stars that have evolved into red giants, a strange phenomenon called *electron degeneracy* develops. Electron degeneracy is important not just for the behavior of stars that become red giants but for understanding white dwarfs. The phenomenon of degeneracy of electrons has to do with the fact that each and every electron in the universe is indistinguishable from every other electron. The rules of quantum mechanics dictate that two identical particles located in the same small volume of space cannot have the same exact properties. As a result, if in one place inside a star one electron already exists with a given energy and motion and spin, another electron with the same properties cannot be forced by gravitational pressure into that same volume of space, even if the pressure is otherwise high enough for this to happen. This uncollegial pattern of behavior, like a game of musical chairs with far more players than chairs, is known as the *Pauli exclusion principle*.

Unlike a regular game of musical chairs, however, the players who do not get chairs are not sent home; instead, they continue to mill around the filled chairs, filling the rest of the room. And because the roaming players fill the walking space left in the room, they prevent other potential players from even entering into the room.

When the gas at the center of a star is subjected to enormous pressure, it becomes degenerate. The gravitational pressure from the outer layers of the star prevents degenerate electrons from leaving the degeneracy region, just as a line of players might crowd the door to the musical chairs room, preventing those players without seats from leaving that room. If our game of musical chairs became a marathon, dragging on for days, our players would become exhausted; they would walk more slowly; they would desperately want to sit down. But with no chairs available, they would have to continue to stand, to wander around the room, and they would continue to fill the room and prevent new players from coming into the room. The human pressure that would fill this room would no longer depend on the decreasing energy of the players (equivalent to the temperature of a gas) but would now depend on the mere existence of too many players in too small a place (which we can associate with the pressure of the degenerate gas).

At the high densities and temperatures near the centers of red giants, all the electrons act like a cloud. And the cloud of free electrons is squeezed into such a small volume that the electrons eventually fill up all the available low energy states — all the chairs are taken. Gravitational pressure tries to squeeze even more electrons into this small volume, but the Pauli exclusion principle prevents this from happening. The electrons remain at higher energies (equivalent to higher temperatures) than they would normally have. Consequently, the extra electrons, hot, confined and highly pressurized, push back against gravity. The pressure exerted by these electrons is known as *degeneracy pressure*. And so, at the cores of red giants lie, hidden from view, degenerate cores. These degenerate cores, once exposed to space, are called *white dwarfs*. White dwarfs are the final end-state for all stars that, when they die (after the planetary nebula phase, discussed later), have masses of 1.4 times the mass of the Sun or less.

White dwarfs are truly bizarre objects whose characteristics are extremely remote from anything we experience in everyday life.[4] Though they have high surface temperatures, they also have very small surface areas (about 10,000 times less surface area than the Sun since they are about the same physical size as the Earth). Consequently, they are very faint.

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[4] While the phenomenon of electron degeneracy develops at the extreme pressures and densities at the centers of stars, degenerate electrons also exist in normal metals on Earth. Degenerate electrons are responsible for the high electric and thermal conductivity present in metals. The presence of the degenerate conduction (free) electrons in metals makes metals very difficult to compress. In fact, a good analogy to a white dwarf would be a ball of liquid metal. Qualitatively, the difference between a white dwarf and the liquid metal ball is the enormous density and pressure of the white dwarf, so that there are more degenerate electrons in a given volume in the white dwarf than in the liquid metal ball.

A typical white dwarf is about the size of the Earth but has the mass of the Sun (about 300,000 times more mass than the Earth). This combination of small size and large mass means that the average density of a white dwarf must be about 300,000 times greater than the average density of the Earth, upwards of one ton per cubic centimeter, and that the gravitational force at the surface of a white dwarf must be 300,000 times greater than the gravitational force at the surface of the Earth. At such high densities and pressures, almost the entire volume of a white dwarf is filled with degenerate electrons. A white dwarf, then, is an earth-sized sphere comprised of helium, carbon, and oxygen nuclei that is filled with a fog of degenerate electrons.

The radius of a white dwarf is determined by electron degeneracy pressure, not by its internal temperature. No matter how much energy the white dwarf radiates into space, no matter how cool it gets, a white dwarf will stay the same size. Gravity has forced the state of degeneracy on the white dwarf but cannot compress the star any further. Finally, and forever, gravity has lost. And so, billions of years in the future, much of the mass of the universe will be permanently locked into cooling white dwarfs.

Because white dwarfs are small, they do not emit much light compared to stars. Such objects are difficult to detect even if they are near the Sun. In order to find white dwarfs, astronomers need large telescopes to collect enough light.

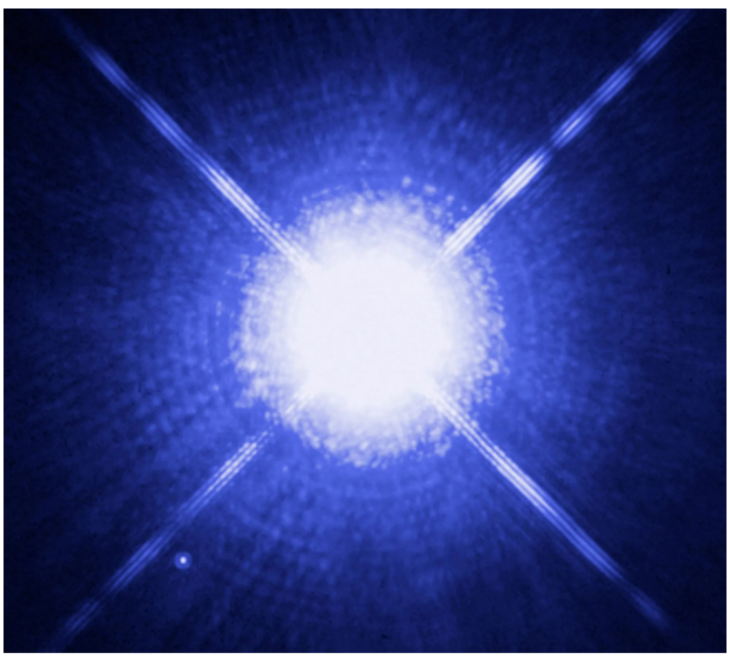

Figure 6: Hubble Space Telescope image of Sirius (the bright star in the middle) and its white dwarf companion Sirius B (seen in the lower left of the image). Credit: NASA, ESA, H. Bond (STScI) and M. Barstow (University of Leicester)

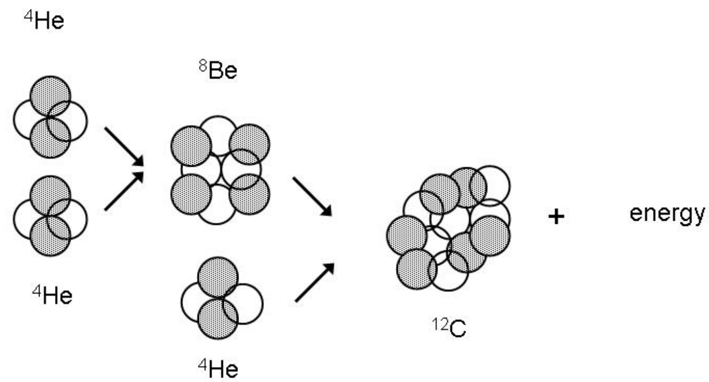

Figure 7: The triple-alpha process for nuclear fusion. Three helium nuclei combine, through a series of intermediate-step collisions, to form a single carbon nucleus and release energy as gamma rays.

Red Supergiants

When the temperature of the core reaches the incredible temperature of about 100 million K, helium nuclei are moving fast enough to collide with each other. When the density of the core surpasses 10^4 grams (10 kilograms) per cubic centimeter the helium nuclei can no longer avoid collisions. Nuclear fusion of helium nuclei into carbon nuclei begins.

The helium fusion process occurs in two steps. First, two ^{4}He nuclei collide; they stick together and form a ^{8}Be (beryllium-eight) nucleus. Some mass is converted to energy, and this energy is released as a gamma ray. The ^{8}Be nucleus, which contains four protons and four neutrons, is very unstable (^{9}Be, with four protons and five neutrons, is stable, but normal stars make ^{8}Be, not ^{9}Be) and quickly falls apart into two ^{4}He nuclei; however, at temperatures of 100 million K and above, the rate at which ^{8}Be can form is comparable to the rate at which it falls apart, so some ^{8}Be nuclei survive long enough to participate in the next step in this fusion process, in which a third ^{4}He nucleus collides with a ^{8}Be particle to form a ^{12}C (carbon-twelve) nucleus, containing six protons and six neutrons.

Because, for historical reasons, the helium nucleus is referred to by physicists as an alpha particle, and because this process ultimately turns three alpha particles into a single carbon nucleus, this process is known as the triple-alpha process. Along with the triple-alpha fusion process, stars more massive than the Sun turn a little bit more mass into energy by producing a small amount of oxygen through a reaction in which a ^{4}He nucleus collides and combines with a ^{12}C nucleus to create an ^{16}O (oxygen-sixteen) nucleus. Slowly but surely, the cores of these stars fill with helium, carbon, and oxygen, with some of the carbon and oxygen mixing upwards into the outer layers of the star.

The internal structure of aging stars with large masses begins to resemble an onion. They have inert central cores in which newly formed carbon nuclei are accumulating.

Surrounding the mostly inert carbon cores, they have shells of helium in which helium-to-carbon fusion occurs; surrounding these shells, they have thin shells in which hydrogen fusion is generating more helium. Outermost, they have inert shells of hydrogen in which the hydrogen is too cool for fusion. As they age, they once again expand and become more luminous, ultimately becoming red *supergiants*.

Planetary nebulae

One of the consequences of a star puffing up into a red giant or red supergiant is that it sometimes expands in size so quickly that gravity cannot slow down the outward rushing shell of gas enough to stop it and hold on to it. Instead, the envelope escapes from the star, like a smoke ring puffed off into space. After enough puffs, all that is left behind is the extremely hot and small core — the white dwarf — of the red giant. The material pushed off into space is called a *planetary nebula*.

Red giant stars are very effective at puffing off these rings at speeds of thousands of kilometers per second and at high mass-loss rates. Virtually every star in the mass range from half to about nine solar masses will end up shedding all but about half a solar mass during this phase. While these dying stars are actively expelling their outer layers into space, they are called planetary nebulae because, to astronomers with telescopes 200 years ago, these objects appeared big and circular, looking very much like fuzzy planets and very unlike stars, and also because early spectroscopists recognized that these fuzzy round nebulae were not solid bodies like planets but instead were made of gas. At temperatures of up to 150,000 K, the left-behind cores are white hot and emit far more ultraviolet than visible light. The ultraviolet light heats up the escaping planetary nebula gases and causes these nebulae to glow.

When these stars die as planetary nebulae, much of the helium, carbon and oxygen they generated in fusion reactions will be expelled into space. While the exposed cores will be left behind and will become white dwarfs, these expelled atoms will become parts of molecules and dust grains that will collect into interstellar clouds and then form into the next generation of stars and planets. In this way, each generation of red giants enriches the interstellar medium with elements that are heavier than hydrogen. Ultimately, all of the carbon atoms on earth, whether in coal, graphite, diamonds, organic molecules, or carbon dioxide, and all of the oxygen we breathe was manufactured in the cores of red giant stars.

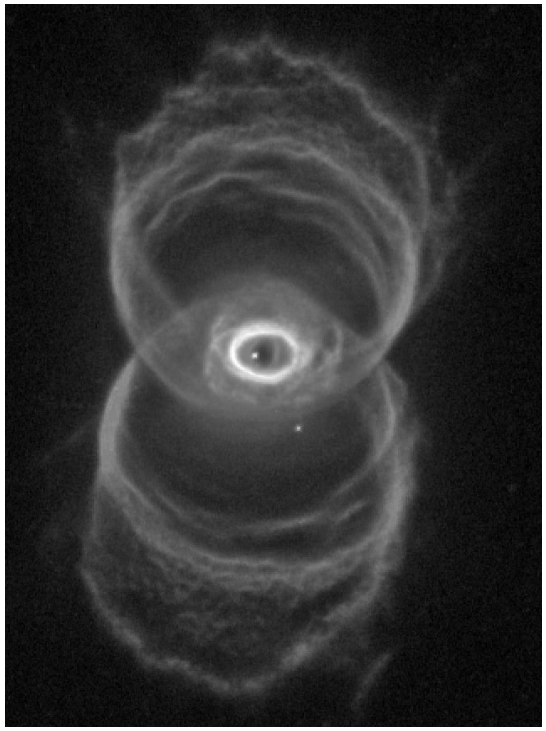

Figure 8: Hubble Space Telescope image of Cat's Eye planetary nebula. (courtesty of NASA, ESA, HEIC, and The Hubble Heritage Team (STScI/AURA))

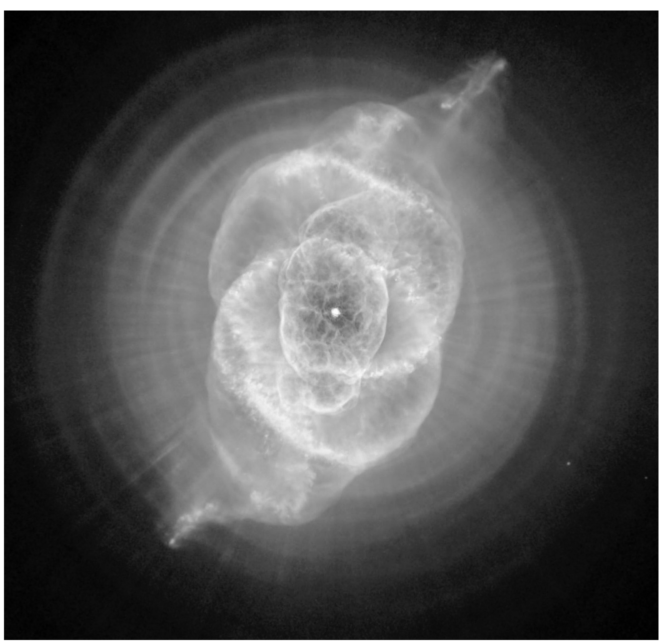

Figure 9: Hubble Space Telescope image of the Hourglass planetary nebula. (courtesy of Raghvendra Sahai and John Trauger (JPL), the WFPC2 science team, and NASA)

Neutron Stars

What if the final mass of a stellar remnant, after the planetary nebula phase, is greater than 1.4 solar masses? In such cases, electron degeneracy pressure is not enough to resist gravity. The force of gravity crushes the electrons together with the protons to make neutrons. All that remains is a sphere of neutrons with a diameter of about 10 kilometers. Such an object is a *neutron star*. Now, the pressure that resists gravity is neutron degeneracy pressure.

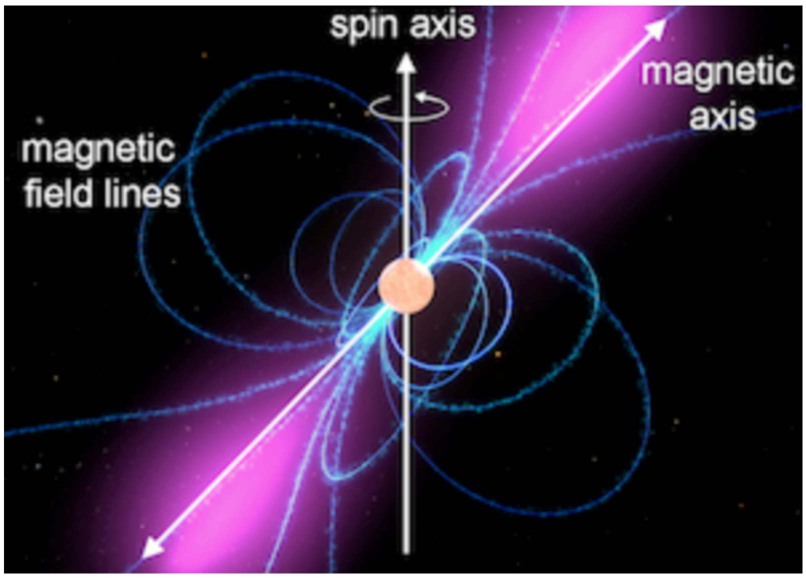

Figure 10: This diagram of a pulsar shows the neutron star with a strong magnetic field (the loopy lines) and a beam of light emitted along the magnetic axis. As the neutron star spins, the magnetic field spins with it, sweeping the beam in a circle through space. If the beam sweeps over Earth, we see it as a regular pulse of light. (Credit: NASA)

As the stellar core is crushed from supergiant size to white dwarf size all the way down to the size of a small city on Earth, it spins faster and faster. And so neutron stars spin astoundingly fast, some as fast at several thousand times per second. These spinning neutron stars emit energy from their north and south magnetic poles, and since the north-south magnetic axis is typically not aligned with the north-south rotational axis, these beams of light spin around like the light beams from a lighthouse. If the direction of the beamed light is pointed in the direction of Earth, the neutron star appears to turn on and off, over and over again, like a pulsing flashlight, even though the emitted light is not pulsing. The first neutron stars were discovered by Jocelyn Bell Burnell in 1967 and were dubbed *pulsars*. The fastest spinning ones are known as millisecond pulsars.

Black Holes

Even neutron degeneracy has a limit. If the mass of the stellar remnant is more than about three times the mass of the Sun, the gravitational pull crushes the neutrons into each other. The resulting object becomes so small that the gravitational pull at its surface becomes so great that nothing thrown or beamed upwards from the surface can escape. Since nothing in the universe can move faster than the speed of light, and since the escape velocity from this object is greater than the speed of light, this object cannot be seen. It is a *black hole*.