Chapter 2
Where Does Helium Come from?

Cosmic Abundance

Hydrogen and helium are the two most abundant elements in the Universe. As a matter of fact, the entire cosmic inventory of hydrogen and helium make up over 98 % of all known matter in the Universe. The remaining 2 % amounts to every other element combined. Despite the fact that our Earth is a rocky planet and contains an abundance of additional elements like oxygen, silicon, and iron, for example, it is not representative of the entire Universe. Our planet Earth, in the grandest of grand schemes, is nothing more than a speck of cosmic dust revolving around a medium sized star. It is not until we take the Universe as a whole until we can understand just how much hydrogen and helium exists out there.

A hydrogen atom is the simplest element on the periodic table because its nucleus is nothing more than a single proton which is orbited by a single electron. It is number one on the periodic table and is, by far, the most abundant element in the Universe. If we break the hydrogen atom down we are left with a single, lonely proton. This single proton in the nucleus identifies the element as hydrogen because the number of protons equal the element's atomic number. It is this atomic number which identifies each specific element. Helium, for example, has an atomic number of two because it has two protons. As we add another proton to a nucleus, it becomes a different element. There are 92 naturally occurring elements from atomic numbers 1 (Hydrogen) to 92 (Uranium). Helium has two protons, two neutrons, and two electrons.

Leaving neutrons out for a moment, helium has two protons which are nothing more than two hydrogen nuclei. As we venture down the periodic table, every unique element has varying quantities of hydrogen nuclei in their own nucleus. Everything around us was born from the nucleus of hydrogen atoms (protons). Thus, everything starts with the simple proton and this is where we will begin

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the explanation of helium's abundance in the Universe. In order to see just how helium came to be, we need to start at the very beginning to an event called the Big Bang, or the birth of our Universe.

The Big Bang

The Big Bang is the prevailing theory about the birth of our Universe which theorizes that as we go back in time nearly 14 billion years, all energy and matter can be reduced to an infinitesimal point, called singularity. To clarify even further, when we think of this explosion, we are not talking about an explosion *in* time but rather *of* time. To ask the question what happened before the Big Bang would be meaningless because time did not exist before the event. In addition, this "point" was not in any specific location but it was everywhere at once. There was no medium in which the universe exploded in, rather it was the explosion of the medium itself. Although this is a difficult concept to grasp given our perceptions of such an event, it is nonetheless an important concept. Everything that we see today started from this single event of unparalleled proportions. All of the matter that ever existed and ever will be was created from this single event and as the Universe evolved, the matter from the initial Big Bang would transform into the elements we see today.

In order to understand the nature of singularity or the single point where space and time began, think of it this way: if we took the entire Earth, all of the other planets in our solar system, our Sun, our Milky Way galaxy containing hundreds of billions of stars, and every galaxy each containing hundreds of billions of stars, and hit the reverse button to nearly 14 billion years ago, everything would fit into a point the size smaller than an atom. Of course, this is no ordinary atom, it is the primeval atom which had infinite energy and temperature. It is the point from which everything we see today came from. From this infinitesimal point of energy, all matter was created.

Although we don't know how or why the Big Bang occurred some 14 billion years ago, scientists have a fairly good notion of what happened in the moments immediately after it occurred. By immediately, we mean we know the probable events all the way up to 10^{-43} s after space and time began. Just to give you an idea in visible form just how small this value is, this is the equivalent of 0.0000000 000000000000000000000000000000000001 s. The period from zero to 10^{-43} s is known as the Planck era, named after the father of quantum theory, Max Planck. Not much is known over this incredibly small period of time because no current theory exists that can adequately explain it but we do know that our four elementary forces of nature (gravity, electromagnetism, strong force, and weak force) were unified and thus only one force of nature existed. Nevertheless, the period after 10^{-43} s is fairly well known as the universe started to expand and cool.

After the Plank Era, or between 10^{-43} and 10^{-35} s, we know that the universe, which had already expanded and cooled dramatically (but still a very hot

10^{32}–10^{27} K), was principally full of radiation (energy). During this period, gravity was able to precipitate out as the temperature dropped and subatomic particles (and their anti-particles) were able to form via a process called pair production. Pair production, explained in an overly simplistic way, is how matter was created directly from energy. To understand how pair production works, it might be easier to explain by using a well known example.

We all know Einstein's equation, $E = mc^2$, which shows the relationship between mass and energy. This formula states that matter is energy and energy is mass. The mere fact that mass and energy are on opposite sides of the equal sign highlights this relationship. It is the "c" in c^2 that shows how much energy mass contains. c stands for the Latin word *celeritas* ("swiftness") and is the symbol for the speed of light. The speed of light is precisely 299,792,458 m/s (or about 671 million miles per hour). Thus, anything multiplied by this number squared is going to be a very large number. As you can see when we plug into the equation, then, the energy equivalent of a small amount of mass is fundamentally huge as is demonstrated, for example, by the explosion of an atomic bomb. Small amounts of matter contain vast amounts of energy.

Just as we see how the destruction of matter can produce massive amounts of energy by using this equation, we can also determine how much energy is required to produce mass. This is how the most fundamental building blocks of matter were created in the Big Bang and we call this process, pair production. Pair production occurs when two photons, which are discrete packets (packets of light) of electromagnetic radiation, merge to create a particle-antiparticle pair. In the case of the moments after the Big Bang, all of the energy in the form of high-energy gamma radiation could form actual matter and antimatter (we will discuss antimatter in a moment). So, from the very beginning, there was nothing more than energy from which we all spawned. This energy ultimately created all of the matter we see today from a galaxy all the way to the book you are holding in your hand.

Before we go on, it is important to understand the definition of energy as it relates to the events after the Big Bang. We are all familiar with the visible light spectrum which is made up of all of the colors of the rainbow. That is, and as will be discussed later in the book, if we took a beam of light and directed it through a prism, we would notice the constituent colors of this white light which range from red to violet. Each of these colors have different energy levels with red having the lowest energy (low frequency waves) and violet (high frequency waves) having the most. The entire rainbow makes up the visible spectrum which we see all around us. The energy levels above and below the visible spectrum like infrared and ultraviolet are outside of our visible range and we are not able to detect them without proper equipment. Beyond these immediate ranges, however, lie gamma rays which are the highest energy waves (highest frequency) and radio waves (lowest frequency) which are the lowest. Although humans can only see the narrow range of the visible spectrum, the entire electromagnetic spectrum, visible spectrum included, from radio waves to gamma rays are pure energy (light) and are emitted as photons which are discrete packets of light that have both wave and particle properties. They all move at the speed of light regardless of their frequency thus each can simply be called light rays. Gamma rays are high energy photons while radio waves are low energy photons. Immediately after the Big Bang, only high-energy gamma rays existed which, when the Universe cooled, began to lose energy and fall into other portions of the electromagnetic spectrum (Fig. 2.1).

All of the matter that was created during the Big Bang was formed from high-energy gamma radiation (photons) that was the only form of light (energy) created immediately after the Big Bang. It was these gamma ray photons with unfathomable energy which created the matter we see around us. As mentioned in the previous paragraphs, it takes an enormous amount of energy to create matter and it was these high-energy gamma ray photons which allowed this to happen. Any lower energy photon would not be able to create matter which is why all the matter in our Universe was created immediately after the Big Bang.

Getting back to the formation of matter from energy, we are now able to see how pair production occurs due to the incredible energies surrounding the moment of the Big Bang. In a moment we will discuss the types of particles created via pair production but first it is important to understand anti-particles (anti-matter) which created with equal quantities after the Big Bang.

For those who are unfamiliar, antimatter is the precise opposite of matter. For instance, an electron is a negatively charged form of matter and is the smallest elementary particle we know of. Its antimatter opposite is called a positron. Both an electron and positron are absolute mirror images of one another except that that a positron is positively charged. They are the same size, have the same mass, and are otherwise completely identical. Interestingly, when matter meets its antimatter opposite, they annihilate one another in a flash of energy to produce photons, or electromagnetic radiation (light). Put another way and in human form, we are all made up of matter. If we could somehow walk out the door and meet our antimatter opposite, we would look absolutely and completely identical in every way. If we were to shake hands with our antimatter opposite, however, we would both completely disappear and transformed into a burst of pure energy in the form of electromagnetic radiation.

The early universe created equal amounts of matter and antimatter. A question might arise, then, if matter and anti-matter annihilate one another, how is there any matter in the universe? It is a very good question and there is really no way to explain it other than somehow we ended up with a slight imbalance of more matter than antimatter and theories for this phenomenon are beyond the scope of this book. The fact that we are here means that matter prevailed over antimatter. One of the most amazing things about the Big Bang is that most of the matter and antimatter that were created in the moments after the Big Bang were annihilated. We are all products of that small amount of matter that somehow survived.

By the end of 10^{-35} s, the strong nuclear force (the force that binds an atomic nucleus together) began to precipitate out into its individual form but it is also in this time in which astronomers believe that dark matter became apparent. The subject of dark matter is also too vast to go into any great detail here but in the beginning of time, it was less important. As the universe aged, it has become much

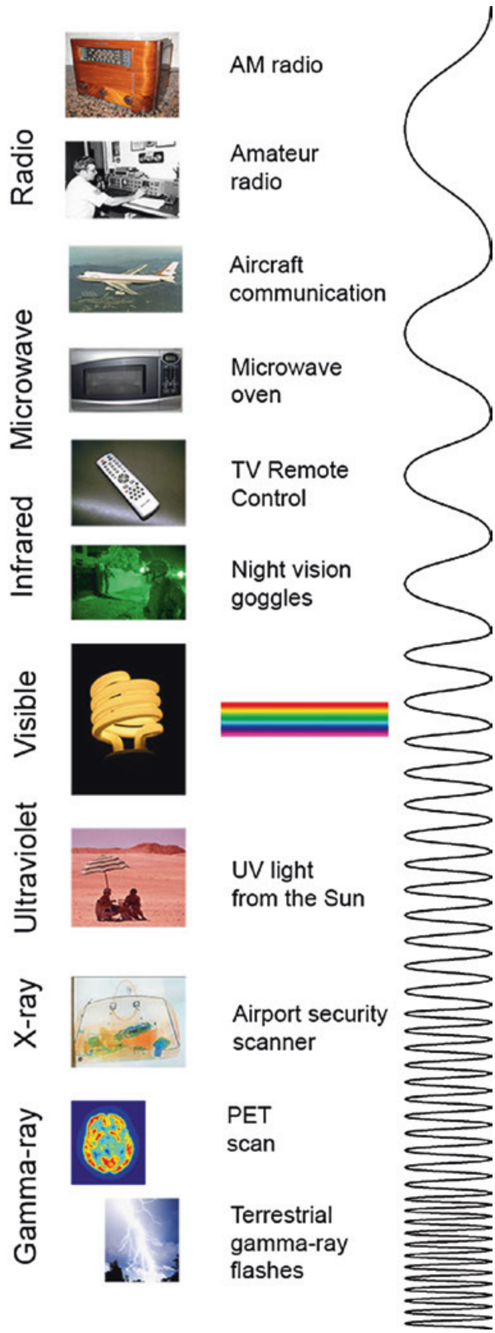

Fig. 2.1 Electromagnetic spectrum. *Source* NASA

more important because it comprises the vast majority of density in the universe which holds our galaxies together but scientists have found very little evidence beyond theory.

In the period between 10^{-35} and 10^{-4} s after the Big Bang, the heavier elementary particles such as protons and neutrons, and their antimatter opposites, formed via the pair production process mentioned above. These heavier particles were the first to form because of the higher temperatures and higher energies of the photons. Greater energy resulted in more massive particles like protons which are 2,000 times more massive than electrons. Most of these particles created during this time were annihilated, however, converting their mass back into photons where the chain reaction would continue until there was nothing left but slightly more matter than antimatter. It was also during this time when both the weak nuclear force and the electromagnetic force precipitated out thus releasing the remaining individual components of the forces of nature.

By the time we fast forward to about one second after the birth of the universe, electrons and positrons (the electrons opposite) were formed by pair production and, once again, most of these particles were annihilated much like the earlier and heavier protons and neutrons. Electrons and positrons, which are elementary particles, required far lower temperatures and subsequently lower energy photons hence the low mass of the electron (and positron). After the end of this first second, all the matter formed through pair production resulted in all of the known matter in the universe. After the universe cooled below 10^{12} K, pair production was no longer possible because there was not enough energy to produce matter as the temperature after expansion had dropped even further. Thus, the principal building blocks of matter were all manufactured within one second after the Big Bang.

After about 100 s (just over a minute and a half) after the Big Bang, protons and neutrons (the ones that were not annihilated) started to fuse into the heavier "nuclei" like helium (only the *nuclei* of protons and neutrons had formed by this time). This fusion process happened very quickly while the Universe was still hundreds of millions degrees Kelvin. Electrons could not attach to a nucleus until later due to the still extremely high temperatures that would otherwise tear off electrons from a nucleus. Within 15 min, however, conditions cooled to the point where the fusion process ended after which virtually all of the helium nuclei in the entire universe had already been formed.

From a minute until about 300,000 years after the Big Bang, radiation was still the predominant make-up of the early universe and this radiation (photons) would continue to break up nuclei as fast as they could form. The early universe was a soup of radiation, hydrogen and helium nuclei, and a vast array of electrons. Photons would break up nuclei and create more photons, which would go on to break more nuclei. Light (photons) could not travel a straight line because of the temperature and the state of the universe was still a radiation-filled plasma soup where photons would be absorbed by other photons only to be broken up again. After 300,000 years, however, the "radiation" era of the Universe ended and cooled to the point where electrons could latch on to nuclei and form full-fledged atoms. Once full atoms were created after the radiation era, larger structures such as galaxies and stars (and ultimately planets) could form from the grouping of atoms.

On a cosmic scale, virtually all of the helium that was ever created was born in the Big Bang. The Universe is still predominantly hydrogen and helium that was created in the first moments of time and space. After the Universe was around 200 million years old, hydrogen and helium gas clusters would go on form large clumps of gas where gravity would take hold and form the first generation of stars and galaxies. Stars were born when large clusters of hydrogen and helium gas would fall under the weight of its own gravity and compress to the point where their core temperatures and pressures were high enough for perpetual hydrogen fusion reactions could occur. This reaction, as can be seen on our own Sun, is a process called the proton-proton exchange in which hydrogen is fused to produce helium. Thus, our Sun, along with virtually every star you see in the night sky is a giant nuclear, helium-producing, life-giving, furnace.

The Sun

Our Sun is a very important topic when considering helium for two reasons. First, enormous amounts of helium are created every second in the core of the Sun via hydrogen fusion and second, the Sun is where helium was first discovered many years before it was ever discovered on Earth. The purpose of this segment is to discuss the process by which the Sun produces helium but also give the reader a thorough understand as to *why* helium was detected on the Sun in the first place. Both points can be addressed by the process that occurs in the very hot and dense core of the Sun.

Breaking down the composition of our Sun by *mass*, ~75 % is hydrogen and ~25 % is helium which, as you learned in the segment about the Big Bang, is roughly the composition of our Universe (of course, we are only including visible matter and are not including dark energy or dark matter). The principal composition of our Sun is primarily the product of the material produced during the Big Bang. Interestingly, about 99.86 % of all of the mass of our solar system is housed completely in the Sun while the giant planet Jupiter has about 66 % of the rest of the mass. Everything else in our solar system, Earth included, only comprises 0.05 % of the entire mass in the solar system. Thus on a cosmic scale, our Earth is quite small indeed!

The Sun is a star, just like all of the stars visible to the naked eye on any clear night. Indeed, if you look at the stars at night, they all shine through the same process that occurs in our own Sun. This process, nuclear fusion, is at the heart of every star turning matter into energy much like energy creating matter in the moments after the Big Bang. Recall that energy and mass are on opposite sides of the $E = mc^2$ equation which highlights the relationship between mass and energy.

Our Sun is a second or third generation star that formed from the debris of stellar explosions before it. Although we will go into greater detail about these stellar explosions (supernova) and subsequent star formation later, what is important to understand that stars are born and die. There is a beginning and an end during the ever evolving state of our Universe. Our Sun was born roughly five billion years ago and will ultimately fade into existence in another five billion years.

What does a second or third generation star mean? About 200 million years after the Big Bang, large clusters of hydrogen and helium began to form creating large structures like stars and galaxies. These first clusters of gas which formed stars and galaxies were made from the only raw material the Universe had to offer in the early Universe, hydrogen and helium. These early stars were massive, hundreds of times more massive than our own Sun. The result of these larger sizes meant that these stars burned enormous amounts of hydrogen via nuclear fusion and consequently ran out of fuel faster than a smaller star. After these early stars ran out of hydrogen as their primary fuel source, the cores would become hotter resulting in the burning of helium created from the initial hydrogen fusion process (this process will be discussed in much greater detail later). Needless to say, once the helium fuel ran out, carbon was created. This process continues where the nuclear ash created in the previous reaction is used as fuel for the next stage of a stars life all the way up to the creation of iron when the fusion process ends. Once these early stars' cores contained iron in their core, they would explode in an event known as a supernova which is an event of unparalleled proportions scattering all of the elements up to iron into the Universe while creating new elements in the process. Thus, most of these "first generation" stars left material for second generation stars to form. When second generation stars explode, material is left for third generation stars.

Our Sun was formed from the debris left over from a previous supernova (or additional supernovas). We know this to be the case because when we analyze the composition of the sun via spectral analysis, many elements are present such as oxygen, carbon, nitrogen, silicon, magnesium, neon, iron, sulfur, and many others. However, the primary composition of our Sun is still hydrogen and helium (by far, the most abundant elements in the Universe) which represents 91.2 % and 8.7 % respectively from the standpoint of the total number of atoms in the Sun. The remaining 0.1 % represents everything else combined. There mere presence of these other elements means that our Sun was formed from the stellar debris of a previous supernova(s).

Although iron is the last element created via nuclear fusion in stars, once a star goes supernova (a very rare event with second and subsequent generation stars), all of the other elements up to the last natural element, uranium, are created in the explosion itself via *fission*. So, where elements are fused together (fusion) in the main portion of a stars life, fission (or the breaking up of atoms) is the process by which the heavier elements are formed. This topic will be discussed in greater detail later. These other heavier elements are also found in our Sun but in much lesser amounts as one would expect due to the rare event of a supernova. Our Sun, being an average sized star, will not go supernova but will rather simply fade away at the end of its life. Only massive stars go supernova and our Sun is a very average sized star.

Now that we know how our Sun (and by proxy all other stars) formed from the debris, we can begin the topic of how nuclear fusion takes place in the core of our Sun (and other stars). When our Sun formed from the debris of a previous stellar explosion, its mass gained by attracting other nearby material (again, with mostly hydrogen and helium). Once the gas cluster that formed our Sun became large enough, gravity began to pull the material in on itself creating a very dense and hot core. As soon as the pressures and temperature of the core were high enough, the fusion oven turned on and light (energy) was created. At this point, which happened about five billion years ago, our Sun was born.

How does our Sun work and how does it produce helium? Our Sun, on a cosmic level, is a very average star compared to all others in the Universe but as mentioned before, the process that drives our Sun is precisely the same as virtually every star you see in the night sky and, indeed, across the Universe. The nuclear furnace that produces helium from hydrogen in the Sun takes place in its core.

The hottest and densest part of our Sun is the core where the nuclear reactions take place that keep it shining. Inside the core, the temperatures (~15 million degrees Kelvin) and pressures are such that fusion can occur as hydrogen nuclei (protons) are moving fast enough to fuse together. How does that process work? In our Sun (and all stars), during the main period of life called the main sequence, it is a process called the Proton-Proton Chain (or P-P Chain). In larger stars, and in a small effect in our own Sun, there is another process called the C-N-O Cycle (Carbon-Nitrogen-Oxygen Cycle).

The P-P Chain is the predominant method of helium production in our own Sun. It starts with two hydrogen nuclei (or protons) that are moving fast enough to overcome the repulsion of the two positively charged protons and fuse together[1] to form a heavy hydrogen atom called deuteron (^{2}H).[2] The collisions of these protons are nearly head-on and are actually very rare events. Only about one proton in one hundred million protons are even moving fast enough to be able to fuse together. Of that one in one hundred million protons which are moving fast enough to fuse, only about one in ten billion trillion (10^{22}) protons will actually fuse. This means that the average lifespan of a proton in the Sun is about 14 billion years before it will ever fuse with another proton.

The first stage of the P-P Chain is the fusion of two protons. To understand the formula below, we will call each proton "^{1}H" as it is noted scientifically (recall that the hydrogen nucleus is nothing more than a single proton). The one in front of the ^{1}H (Hydrogen) is the atomic weight of the element. As an example, the most common helium atom is written "^{4}He" because the atomic weight of the nucleus is 4 (^{4}He can also be written as Helium-4 and has two (2) protons plus two

[1] At very high speeds, when a proton has a head-on collision with another proton, they become a single nuclei because the strong nuclear force (the force that binds nuclei together) overpowers the electromagnetic repulsion between the two positively charged nuclei.

[2] Deuteron is an isotope of hydrogen that has one proton, one neutron, and one electron.

(2) neutrons thus having a weight of *roughly* 4). Getting back to the start of the P-P Chain, there exists two single protons, one of which turns into a neutron which fuse together to form a heavy hydrogen nuclei called deuteron (^{2}H; one proton and one neutron) while releasing energy in the form of gamma radiation and a neutrino.[3] The next step uses the product of the first stage to create a lighter isotope of helium. In this step, a single deuteron atom (^{2}H) fuses with a proton to create the light isotope of helium (^{3}He) and energy. In the third and final step, two ^{3}He atoms fuse to create ^{4}He plus two protons, two neutrons, and energy (gamma ray photons). In scientific notation, here are the steps:

1. ^{1}H + ^{1}H → ^{2}H + positron[4] + neutrino
2. ^{2}H + ^{1}H → 3He + energy
3. ^{3}He + ^{3}He → ^{4}He + ^{1}H + ^{1}H + energy

In short form, the equation is simply: 4(^{1}H) → 4He + energy + 2 neutrinos.

This reaction is the primary reaction for all stars you see in the night sky (and elsewhere in the universe) and is the principal reaction in our own Sun. There is another reaction that is common in larger stars (and to a much lesser extent in our own Sun) called the C-N-O (Carbon-Nitrogen-Oxygen) Cycle which utilizes carbon as a catalyst that ultimately produces helium (^{4}He) and carbon. We won't bother going into any detail about this reaction because simply because it is not the primary fusion reaction in our own Sun.

The energy released by the P-P Chain is clearly very large but in order to understand just how much energy, we can break it down by looking at a single P-P Chain event listed above. As you learned from Einstein's famous equation $E = mc^2$ which showed how mass and energy are equivalent, we can use this equation to see how much energy is actually produced in this process. The mass of four individual protons (hydrogen nuclei) equals 6.6943×10^{-27} kg. However, the mass of the product, helium, equals 6.6466×10^{-27} kg meaning that a small amount of mass is lost when fusing hydrogen into helium. You may recall from chemistry class the Law of Conservation of Energy and Mass which, very simply states that the sum of energy and mass (matter) on one side of the equation must equal the sum of energy and mass on the other side of the equation. We can lose matter as exemplified by the loss of mass just mentioned in the P-P Chain above as long as this mass is converted to energy. This is precisely what happens in our Sun; the mass that is lost from the fusion of protons into helium is converted to pure energy. This mass lost in a single reaction when multiplied by the

[3] A neutrino (Latin for "little neutral one") is a particle that has no mass or charge and moves virtually undetected through matter. We are constantly bombarded by neutrinos produced by the Sun but they pass through the Earth (and us) as though it was not even there. They are very difficult to detect and can only be found in deeply buried neutron detectors.

[4] Recall that a positron is the antimatter opposite of an electron. Immediately after a positron is emitted, it will interact with an electron (which are extremely abundant) and quickly annihilate in a burst of pure energy (gamma-ray photons). So, energy is released in this first phase of the P–P Chain albeit indirectly via the product of this first stage.

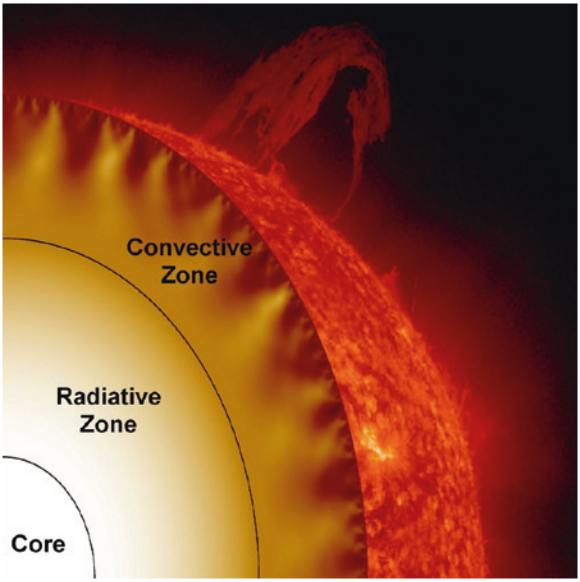

Fig. 2.2 Sun cross section—NASA

shear volumes of converted mass in the Sun produces an extraordinary amount of energy making life possible here on Earth. About 4.3 million tons of matter (the matter that is lost in the fusion process) is converted into energy every second in our Sun. The energy created in the P-P Chain is in the form of high-energy gamma ray photons.

The P-P Chain happens only the core of our Sun where temperatures and pressures are high enough to begin and perpetuate the nuclear reaction mentioned above. What about the rest of the Sun? This is where things get even more interesting and ultimately explains why we even have a visible spectrum which is the only form of light energy humans can detect without additional instrumentation. Surrounding the core of the Sun are several layers each with unique properties that ultimately transport the energy created in the core to the surface of the Sun. Although the detailed mechanisms that happen in these outer regions of the Sun are beyond the scope of this book, immediately surrounding the core is called the Radiation Zone. Other zones away from the Radiation Zone (in order from the core to the surface) include the Convection Zone, the Photosphere, the Chromosphere, and the Transition Zone. Each zone plays an important part in delivering the energy created in the core of our Sun to the surface and ultimately to the entire Solar System (Fig. 2.2).

What is important to note about our layered Sun is that the high-energy gamma ray photons created in the core of our Sun lose energy as these photons make their way to the surface. Gamma ray photons lose energy because most of these photons are absorbed by atoms in the outer layers. As soon as an atom absorbs some of the photons energy, the affected atoms electrons shift to a more excited state which takes some of the energy away from the gamma ray photons. The resulting lower energy photons are then absorbed by more atoms losing more energy along the way. Because of this phenomena, it can take 100,000 years for photons produced in the core to ever reach the surface of the Sun. By the time these photons reach the surface of the Sun to be disturbed across the solar system, the initial gamma ray photons have lost so much energy that the photons emitted are in the visible spectrum. In other words, the very high wavelength (high frequency) gamma rays are spread out to lower wavelength (lower frequency) visible light by the time it reaches our planet.

What happens to our Sun (and stars) when it runs out of hydrogen as its primary fuel? The answer to this question is crucial to understanding why we find helium on Earth which will be described briefly here and in much greater detail later in the book. As we discussed earlier, in about five billion years our Sun will leave what is called the main sequence of its life. The main sequence is the period between when the nuclear furnace begins until it runs out of hydrogen. Most stars are living in the main sequence of their lives because it is, by far, the longest period of a stars life. Our Sun, for example, will live in its main sequence for a total of about 10 billion years. After its main sequence, it will move into what is known as the Red Giant phase when the hydrogen fuel effectively runs out and is replaced by the leftover helium ash from the main sequence.[5] Once the hydrogen runs out, a star (and our own Sun) is no longer in the main sequence of its life and it enters into its elderly years.

After our Sun's main sequence, gravity will pull the core in on itself making it much hotter. Immediately outside the inner core, left-over hydrogen will continue to fuse into helium making the layers beyond the core expand into the orbits of the inner planets of our Solar System. The energy production from helium burning is much lower thus creating a red surface appearance but it will shine about a hundred times brighter than our Sun in its main sequence. The product of helium fusion in the core of the Red Giant is carbon. Immediately outside the inner core, hydrogen fuses into helium no longer by the P-P Chain but rather shifts to the C-N-O Cycle mentioned earlier in the chapter which uses carbon as a catalyst to produce helium. The Red Giant phase of our Sun lasts only a fraction of the time of its main sequence, about 150 million years. After this, our Sun's life will effectively end because there will not be enough heat, due to its average size, to continue nuclear reactions and manufacture additional elements. The only elements that the Sun will produce is carbon, oxygen, and nitrogen. Our Sun will then cool down, lose much of its outer layer material into space, and retire as a cool white dwarf star and simply fade away into existence. The nuclear furnace stops resulting in no more light for our Solar System.

Although our Sun will fade away without providing many elements in the Universe, the same is not true for stars with a greater mass than our own Sun. Indeed, many *smaller* stars will not go beyond the hydrogen burning phase simply

[5] Hydrogen burning will still occur in the outer core of a Red Giant star.

because there is not enough mass to allow gravity to pull itself into create heat required for helium burning. Larger stars, however, have a much different fate. Larger stars continue where our Sun left off creating even more elements because their mass allows gravity to pull in more material to generate more heat. Every sequential element created after hydrogen requires more heat for fusion. Helium fusion requires more heat than hydrogen fusion, carbon fusion requires even more heat, and so on. Thus, greater mass enables these additional reactions.

For stars larger than our Sun, this process continues dependent on the mass of the star but it should be noted that the larger the atomic mass of the element being consumed, the greater energy required to continue the fusion process. Although the actual processes by which this happens is beyond the scope of this book, the sequential products and fuels are as follows: hydrogen fuses to helium, helium fuses to carbon, carbon fuses to oxygen and magnesium,[6] and oxygen fuses to sulfur and neon.[7] After silicon, the primary method of fusion in stars is a process known as *helium capture* where helium fuses with the product of the last fused nuclei. For example, silicon fuses via helium capture to sulfur, sulfur fuses via helium capture to argon, argon to calcium, calcium to titanium, titanium to chromium, and finally chromium to the last elements produced via fusion, iron and unstable nickel which decays rapidly.

After iron, however, fusion can no longer continue because there can never be enough energy to fuse iron which is the most stable element. The internal nuclear reactor stops when the core fills with iron. Energy cannot be extracted either by fusion or fission meaning it is the end of the line for large stars. When a large star reaches this stage, the result is a gravitational inward pull that is so great that the star will ultimately explode in spectacular fashion in an event known as a supernova. The process of supernova will be discussed in greater detail later but these events are responsible for creating all of the other elements after iron and up to the last natural element, uranium.

This is not to say that other elements are not created in massive stars, they are. It is just that the last *fusion* product in a massive star is iron. Other elements up to Bismuth (specifically the isotope Bismuth-209) can be created in stars by process called neutron capture. More specifically, it is called the s-process (s stands for slow). Because there are an abundance of neutrons in these larger stars, neutrons are able to enter the nucleus of many elements without much fanfare. That is, neutrons are electrically neutral so there is no repulsive force from protons fighting

[6] In the carbon stage, two events occur. At extremely high temperatures (~600 million K) and pressures, carbon (12C) will fuse with another carbon nucleus to create magnesium. This process is known as carbon burning. Carbon can also fuse with helium (4He) to create oxygen (16O) and this process is called Helium Capture. Helium capture is far more common because it requires lower temperatures (~200 million K) than carbon burning.

[7] Oxygen (16O) can fuse into another oxygen nuclei to form sulfur (32S) at the extremely high temperature of about 1 billion K. The more common oxygen reaction, however, is also via Helium Capture where oxygen fuses with helium to become neon (20Ne) which occur at lower temperatures.

against their entry. Recall that adding a neutron to an element does not change the element. Rather, it only changes the isotope of the same element. However, with the addition of several neutrons to a single nucleus can make it unstable, forcing it to break up into lighter nuclei. This process, specifically the s-process, is how elements like gold and silver are formed.

It is fascinating to know that all of the carbon in our bodies, the oxygen in our water, the iron in our blood, the nitrogen in our atmosphere, and indeed all of the elements that make up our bodies and the world around us were created in the cores of stars. Early stars used the only raw material available after the Big Bang, hydrogen and helium, and transformed it into the elements we see every day in our lives. Our Universe is a living, evolving machine.

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