Alchemy and the Life of a Star

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There will be two subjects here: the first is alchemy, and the second, the stars. I will explain the connection between these two subjects, but the main objective will be to describe two of humanity's great discoveries. And of course, you will find out how to make gold in abundance!

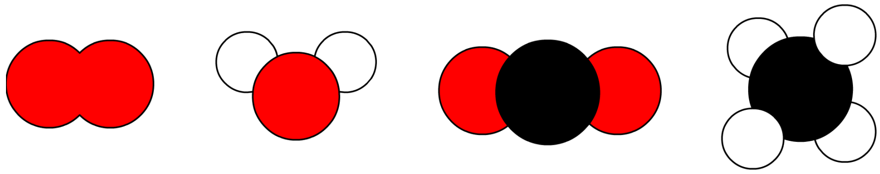
The word 'alchemy' appears in the title and I have just used it again. However, I have no intention of delving into the world of esoterism. Look at this quote from Abu Mūsā Jābir ibn Hayyān, an eighth century Persian polymath, also known by the Latinised name Geber (see Fig. 1):[1]

Figure 1: Geber (721–815 ApJ), an Arab alchemist, famous for his teachings on the transmutation of metals. Twelfth century portrait, Codici Ashburnhamiani 1166, Biblioteca Medicea Laurenziana, Florence. Image public domain

> I see that some people trying to synthesise silver and gold are working in complete ignorance, using false methods. They could be divided into two groups: the cheats and the cheated. I pity them all.

And we, too, may pity them, because they had no hope of success, as we shall soon see. What's more, Geber put his finger on a key problem: ignorance! Because what is alchemy? Transmutation of the elements. For example, the transmutation of lead into gold. But how could anyone transmute lead into

[1] See www.wdl.org/fr/item/10675/



Dioxygen Water Carbon dioxide Methane

Figure 2: *Left to right*: (1) the oxygen we breathe, an association of two oxygen atoms, (2) water, comprising two atoms of hydrogen attached to one oxygen atom, (3) carbon dioxide, invisible and insidious component of the atmosphere, consisting of two oxygen atoms attached to a carbon atom, and (4) methane, which we burn (see later), comprising four hydrogen atoms attached to a carbon atom. Image from the website `physique-chimie-college.fr/definitions-fiches-science/` under the heading 'molecules'

gold without knowing what these things are? What is lead when it comes down to the details? And gold?

So to begin with, let's ask this: what is an element? Today we usually speak about chemical elements and my first task here will be to describe our modern understanding of matter, in a rather qualitative manner. So, of course, we should start with molecules. A few well known molecules are shown in Fig. 2. Some molecules are much bigger and more complex than these, such as proteins, which are the basic building blocks for biological cells, and DNA, which contains our genetic heritage.

In every case, a molecule is an association of atoms. And each atom is a basic chemical element, appearing in the periodic table (see Fig. 3). So this is the first great discovery I want to describe. Look at how much information is brought together in this small space! Today, we know every element that can exist, and even quite a few more that can't exist naturally. This particular table shows 118 elements. In principle, we also know all their properties because we have a theory about atoms, the *quantum theory*, which is basically the theory of the atom.

In the first part of this presentation, my aim will be to explain something about the way the elements are organised in this table, and also to explain in what sense it is periodic. The starting point is therefore the atom, and when we say 'atom', we immediately think of Democritus, another polymath but Greek this time, who lived from 460 to 370 BCE. Take a look at this quote, passed down to us from several sources:

> By convention sweet and by convention bitter, by convention hot, by convention cold, by convention color. But in reality atoms and void.

Here was a truly revolutionary idea! Today we refer to this view as *reductionism*. It's the idea that everything reduces at the end of the day to certain basic building blocks. These building blocks are both very simple and very small.

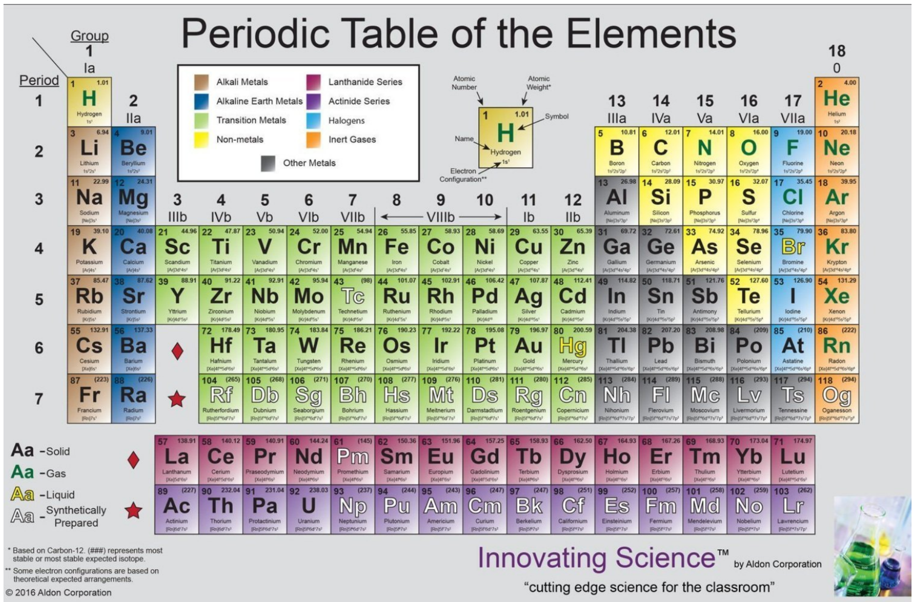


Figure 3: The periodic table of the elements. All naturally existing elements are shown here, and quite a few more (118 elements). Image from the website `www.arborsci.com/products/periodic-table-of-the-elements-poster-size`

The idea of reductionism is a very powerful one and has long motivated science. Indeed, it remains the secret of its success in a great many different areas today.

Actually, if we interpret this translation literally, even the sensations revealed by our senses must reduce to atoms and void. We can almost hear Democritus whispering across the ages, perhaps with his characteristic laugh: "Convention human being"! This is a much debated subject today. In a less ambitious interpretation, the notion of taste is today explained by an interaction between the molecules and certain cells on the tongue, then signals carried by nerves to the brain. And if we understand 'hot' to mean 'high temperature', we explain it by the varying degrees of agitation of the particles making up the object in question. While the colour of an object has something to do with the differing wavelengths of light it can emit.

Today is without doubt the heyday of the atom. We talk about them more than ever before and they play a role very similar to the one imagined by Democritus. But with one important difference: our atoms can be split. And they can be split in two different ways, as we shall see: one easy, the other difficult. Because the atom has two levels of structure.

At the first level of this structure, an atom comprises a nucleus with electrons moving around it (in some way, determined by quantum theory). Look at the hydrogen atom shown in Fig. 4. This is the simplest atom, just because there is

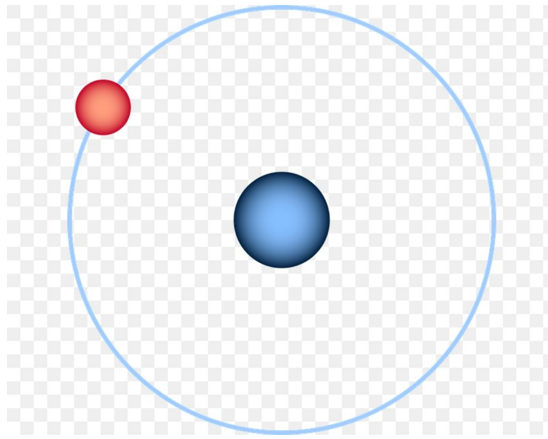


Figure 4: The hydrogen atom is the simplest of all. Just one electron (*red*) moving in some way around the nucleus (*blue*)

only *one* atom 'going round' the nucleus. The scare quotes in the last sentence indicate that this is just a simplified way of thinking about things. But first things first, we should ask why the electron actually remains there in the vicinity of the nucleus.

A planet does something like this. It revolves around its star. It does this because there is an attractive force between the two bodies, the force of gravity. This is also true in the atom. There is an attractive force, but this time it's the electric force. The nucleus carries a positive electric charge and each electron carries a negative electric charge. Then the rule for the electric force is that, when one particle carries a positive electric charge and the other a negative electric charge, the two particles will attract one another. So this is why the electron remains close to its nucleus, at least under normal conditions.

While we are on the subject of the electric force, there is another thing that will be worth knowing in what follows. When two particles carry electric charges *of the same sign*, these two particles will repel one another. What's more, the repulsive force will increase as the two particles come closer together, and it will become very strong when they get very close. This would be true of two atomic nuclei, since each carries a positive electric charge, but also for two electrons, but it is the case of the two nuclei that will be important later on.

Let us just go a little further along this road, because the details are important, even if a little tedious at times. Every atom is electrically neutral, by which I mean that the total electric charge on the atom is zero. For example, the charge on the nucleus of a hydrogen atom is $+1$ and the charge on the electron is -1, whence the total charge is $1-1=0$. The second simplest atom is helium. In this atom, there are two electrons and the charge on the nucleus is $+2$, so the total charge is once again $2-2=0$. The third simplest atom is lithium, with an electric charge $+3$ on the nucleus, hence three electrons. And so on and so forth.

The chemical properties of an element come from the number of electrons in its atom, hence the different name for the element depending on that number. When there are 6, it's carbon, with a charge of +6 on the nucleus. With 8 electrons, it's oxygen. So already in contrast to the idea put forward by Democritus, there are many *different* atoms in our modern way of understanding things. I will return to this idea below.

But first let us pause for a moment to think about the size of these objects. First of all, an atom is something very small. On average, an atom measures something like 10^{-10} m, which means that we would need to line up about ten billion of them to get a row a meter long. But the nucleus is much smaller still. It measures about 10^{-15} m, which means that it is a hundred thousand times smaller than the atom, making it only one millionth of a billionth of a meter across. To get an idea of this difference between the size of the atom and the size of the nucleus, suppose I represent the nucleus by a golf ball, with a radius of about ten centimeters. Then the electron can wander around over a radius of ten kilometers! And between the two, there's nothing, except of course the electric force field. And the electron is so small that we don't even know how big it is, only that it's at least a thousand times smaller than the nucleus.

But let's get back to the periodic table of the elements. It is often referred to as Mendeleev's periodic table. Dmitri Mendeleev was born in Tobolsk in Siberia in 1834, and lived until 1907 (see Fig. 5). First, a word about his mother, for we may read that Dmitri was the seventeenth child! His father was the headmaster of a secondary school in Tobolsk, but he died young. Apparently, Dmitri's mother took Dmitri to Moscow to sign him up for the university when he was fifteen. But they wouldn't take him in Moscow. Too bad for Moscow! So she took him to Saint Petersburg, where he was accepted. We may say that Mendeleev's mother also contributed to the discovery of this famous table!

From Saint Petersburg, Mendeleev went on to Heidelberg in Germany to work with Bunsen and Kirchhoff. This was the century of the new science of chemistry, kick started by the early work of such great chemists as Robert Boyle in Great Britain in the seventeenth century and Lavoisier in France in the eighteenth. The main task at the time of Bunsen and Kirchhoff consisted in isolating and identifying new substances, and in particular, new elements. So, Bunsen and Kirchhoff would burn these elements and look very closely at the light they emitted, because it turned out that this light contained something like a fingerprint for identifying the element. And this is indeed how astronomers can today identify which elements are present far away from us in space or in the neighbourhood of the stars, for example. This kind of analysis is known as spectroscopy.

In 1863, fifty-six elements had already been discovered. That's almost half those shown in the table of Fig. 3. And every year another element was being found, on average. Now look at what Mendeleev tells us about his discovery:

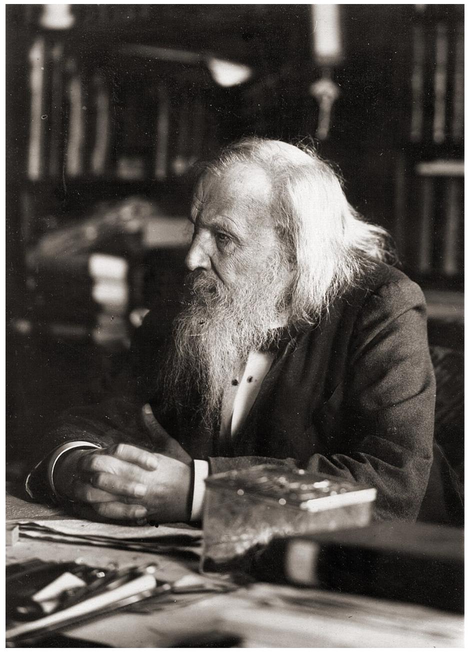


Figure 5: Dmitri Mendeleev, one of the people who contributed to the discovery we are are celebrating here. Image public domain

> In a dream, I saw a table where each element had its place according to its characteristics. When I woke up, I immediately jotted it down on a piece of paper.

Science is so easy, isn't it? However, before having a dream like that, we first need to ponder, meditate on, and generally rack our brains over the given problem for several months, or even years! Then and only then can one bad night's sleep do the trick!

Let us just take a look at what Mendeleev saw in his dream. The first thing was to arrange all the known elements in a row, from left to right, in order of increasing atomic mass. So the first was hydrogen, the lightest. The second would have been helium, only it hadn't been found yet. It was discovered in 1868. The third was lithium, discovered in 1817, then beryllium, discovered in 1798, boron, discovered in 1808, and so on. Except that, from time to time, he would make a line break, as if he wanted to write the list on a rather narrow page. And of course, this line break was not done in an arbitrary way. It was done in such a way that, in each column, all the elements appearing in that column have similar chemical properties. It is in this sense that the table of elements is periodic. Look again at Fig. 3 to see an example. The elements lithium, sodium, and potassium in the first column all react in a similar way with other chemical elements.

However, in order to get this to work the way he wanted, Mendeleev had to leave some spaces in the list. His idea was that there should be elements to fill these spaces. And so it was that, in 1860, Mendeleev predicted the existence of eight elements up to then unknown. Moreover, given the position of each empty space, he was able to estimate the atomic mass of the missing element and even its tendencies to interact with other elements, which was of course extremely useful for those who would try to identify them. Sure enough, shortly afterwards, the missing elements began to turn up.

Mendeleev's contribution was of course very important in this discovery. However, we shouldn't forget the roles played by all the others, the Boyles, the Lavoisiers, the Bunsens, and the Kirchhoffs. Science is without exception a collective enterprise. And it is interesting to note that, according to an article published recently in a scientific journal,[2] the author has found seven people who had roughly the same idea at round about the same time, and probably quite independently. This is something that often happens. This idea was *dans l'air du temps*, as the French would say.

It's important to remember that, at this time, in the mid-nineteenth century, Mendeleev and the others knew nothing of electrons and nuclei. Their work was entirely empirical. There was no theory about the structure of the atom. The electron was discovered by J.J. Thomson in Cambridge in 1899 and the nucleus by E. Rutherford, also in Cambridge, in 1910. The first model of the atom was formulated by N. Bohr during a short stay in Cambridge in 1911. It was the first quantum model of an atom and dealt only with the simplest atom, the hydrogen atom, with its single electron. Bohr gave the first explanation for certain observations of the light emitted and absorbed by matter, the kind of observations that were made by Bunsen and Kirchhoff in the nineteenth century.

But let's take one more look at the periodic table (Fig. 3). Top left, the simplest atom, hydrogen, with it's single electron. The electric charge on the nucleus is $+1$. The second element is top right. That's helium, with two electrons. The electric charge on the nucleus is $+2$. Actually, the electric charge on the nucleus has a name: it's the *atomic number*. These two atoms constitute the first line of the table, and then we do a line break to reach the third element, lithium, with atomic number $+3$, and hence three electrons. As mentioned above, the identity of the element and hence also its chemical properties come from the number of electrons in the atom. The atoms are effectively numbered by their atomic number.

The electric charge on the nucleus, which determines the number of electrons, is equal to the number of protons it contains. And now we are talking about what there is inside the nucleus. We have already seen that the atom is divisible in the sense that we can remove its electrons. But the nucleus is also divisible. It is composed of protons and neutrons. Each proton carries an electric charge $+1$ and each neutron is electrically neutral, i.e., it carries an electric charge 0. This means that the atomic number of an atom, i.e., the electric charge on the

[2]E. Scerri: The discovery of the periodic table as a case of simultaneous discovery. Phil. Trans. Roy. Soc. A **373**, 2097 (2015).

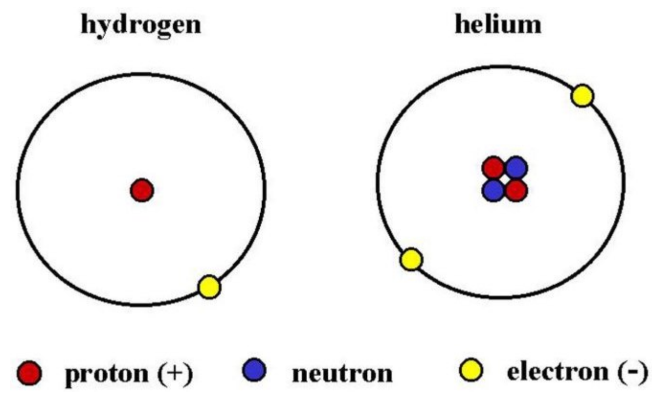


Figure 6: The two simplest atoms, hydrogen and helium. Source: www.humansinspace.org/hydrogen-and-helium-atoms/

nucleus, is equal to the number of protons it contains.

Well, there's an obvious problem here! I already emphasised how small the nucleus is. Just one millionth of a billionth of a meter. And now we're talking about putting particles, protons, which carry an electric charge of the same sign, so very close to one another inside this tiny structure. As I said before, they are going to repel one another, and very strongly, because we are forcing them into such a very small space. If we take two protons and try to force them together, they will repel one another ever more strongly as they move together, and if we then let go, they will simply fly apart, in fact moving faster and faster. However, if we can supply sufficient force, and hence sufficient energy, and if we can manage to bring them to within a millionth of a billionth of a meter from one another, then we will be able to stick them together. This is because there is another force in nature. This is a very short range force but it is truly strong. It is so strong that physicists have, with much imagination, called it the *strong force*!

This force is one of the four fundamental forces of nature, along with the electromagnetic force, the force of gravity, and another force that we won't have time to consider here, the weak force. It is indeed the strong force that manages what's happening in the interior of the nucleus, at these very short distance scales. So to sum up, we may say that, if we can bring a few protons close enough together, they will be able to remain together, with the help of a few neutrons. Because the neutrons are also affected by the strong force, even if they are not affected by the electric force. Indeed, the neutrons play a role in stabilising the whole structure. So finally, since each atom is electrically neutral, for each proton in the nucleus, there will be a corresponding electron going round it.

Look at the examples in Fig. 6. On the left, we have effectively the same image as in Fig. 4, except that there is a little more detail concerning the nucleus. And the nucleus is indeed very simple. It only contains one particle! A proton.

Then there is of course one electron moving around it in some way. The helium atom on the right is a little more interesting, because there are two protons in the nucleus, and then two neutrons are required to stabilise it. What we see here is known as helium 4 (denoted ^{4}He), with two neutrons. The number 4 mentioned here is called the *atomic mass*. There is in fact another form of helium with just one neutron in the nucleus, and this is known as helium 3 (denoted ^{3}He). Note that there are still two protons in helium 3, otherwise it wouldn't actually be helium! As stressed previously, it is the number of protons, i.e., the *atomic number*, which determines the nature of the element.

The atomic mass is the total number of protons and neutrons in the nucleus of whatever atom we are talking about. To give another example, in the case of carbon, there are three possible nuclei. Since we are dealing with carbon, there have to be 6 protons in the nucleus. The atomic number is 6, and there will be 6 electrons. However, there may be 6, 7, or 8 neutrons to produce something stable. When there are 6, we have the commonest form, carbon 12 (denoted ^{12}C). The other forms are therefore carbon 13 (denoted ^{13}C) and carbon 14 (denoted ^{14}C). The latter is slightly unstable, which is why archaeologists can use it to date ancient samples of organic matter (containing carbon).

Let us stop for a moment and ask: what is chemistry? What does a chemist actually do? In fact, she or he breaks up and reassembles molecules. The chemist never breaks atomic nuclei. Look at the example in Fig. 7. Here we see a molecule of methane CH_4 which interacts with two molecules of dioxygen O_2. Indeed, this is what is meant by combustion: the interaction of a substance with dioxygen in the air. Naturally, the reaction has to be triggered by supplying a little energy, in the form of a spark, for instance. But once it has begun, it will deliver energy in the form of light and heat. The reaction also gives some other molecules, different ones: a molecule of carbon dioxide CO_2 and two molecules of water H_2O.

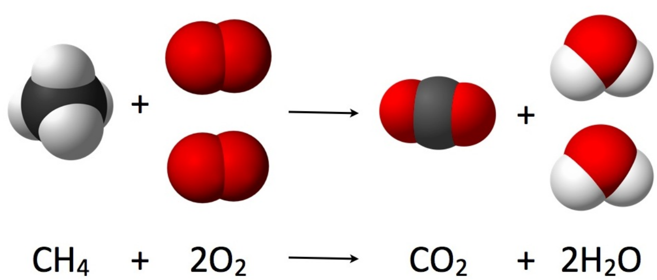


Figure 7: Combustion of methane in dioxygen. See text for explanation. Source: commons.wikimedia.org/wiki/File:Combustion_reaction_of_methane.jpg

So what can we say about this? The first thing, not directly relevant for our present purpose, but interesting anyway, is that there is no smoke! What we see when we burn methane is water vapour. And then there is the invisible and treacherous gas carbon dioxide. But what is important for our present question is to count the different atoms both before and after the reaction. On the left, we see one atom of carbon (the black blob), and the same on the right. On the left, four atoms of hydrogen (the white blobs), and likewise on the right. On the left, four atoms of oxygen (the red blobs), and the same on the right. No atom has been either created or destroyed. They have simply been reorganised to form other molecules.

And now we may ask: what is alchemy? Well, as we said before, alchemy means transmuting one element into another. But this means breaking and reassembling the *nuclei* of atoms. We are now in a position to ask what must be done to transmute lead into gold. Because we now know what lead is, and we know what gold is. Look at the contents of their respective nuclei, which can be read off from the table in Fig. 3:

^{208}Pb	82 protons and 126 neutrons
^{197}Au	79 protons and 118 neutrons

This shows that one must take 3 protons and 8 neutrons out of each lead nucleus. Even if we knew how to do this, it would require a lot of energy, much more than to just break and reassemble molecules. Naturally, this is due to the strong force which controls what happens within these nuclei. The alchemists were effectively chemists, and a chemical reaction is an interaction between elements *without changing* those elements. The alchemists never succeeded in their quest of transmuting elements, and they had no chance of doing so.

In a certain sense, the first alchemist was the Big Bang, which produced hydrogen (H) and helium (He), along with a few small amounts of some other light elements. The Big Bang is our preferred cosmological model today. Indeed, one of the reasons why we prefer it is that it predicts the formation of these two elements, and what's more, in proportions which correspond very well to what is actually observed by astronomers in the Universe, i.e., 75% hydrogen and 25% helium by mass. Matter is composed mainly of H and He. All the other elements taken together only contribute about 1% of the mass of all the visible matter in the stars and galaxies.

But this raises a question: where do the lead and gold come from? Or indeed the iron, which is so common here on Earth? When Cortés asked the Aztecs where they got the iron for their daggers, they pointed to the sky. And they were right! Obviously, they didn't really know why, but you should be able to guess from what has already been said above. Perhaps they were thinking of their gods, or perhaps they had come across a few iron meteorites of the kind that sometimes fall from the sky.

But if we look at the Universe as we know it today, and given what has been said so far in this presentation, it's clear that only the stars could provide the conditions required to mess around with atomic nuclei. This is because very high temperatures and pressures are required, of just the kind that one can easily imagine to hold sway in the heart of a star. We have thus reached the second part of this presentation, which is basically about the discovery of the origin of the chemical elements. And obviously, we shall begin by asking a question: what is a star?

When we admire the night sky, most of the points of light we see are nearby stars in our own galaxy. (There are also a few planets, artificial satellites, and sometimes comets.) The diffuse light that can be made out when there is no source of artificial light to drown it out, which runs right across the heavenly vault, and which is commonly referred to as the Milky Way, is in fact made up of billions of stars in our own Galaxy but too far away to be distinguished by the naked eye. There are after all a hundred billion stars in the Galaxy.

Just by looking for a while at these, we note that the stars have different colours and different brightnesses. To simplify a little, the key for understanding these differences will be the mass of the star. This is what we shall see below. The mass of the Sun is enormous, of course, of the order of a thousand billion billion billion kilos. Astronomers denote the mass of the Sun by the symbol $M_\odot$. And when we wish to speak about the mass of another star, we don't usually give it in kilos, but as a multiple of the mass of the Sun. Twice the mass of the Sun, or ten times, or half, for example. The mass of the star Sirius, for instance, is thus $2M_\odot$.

Stars can also have quite different luminosities. It's important to understand that the luminosity is an absolute quantity associated with the star, unlike the brightness, which also depends to a large extent on the distance of the star. The luminosity is the energy emitted by the star in the form of light each second. In other words, it's the emitted power. The luminosity of the Sun is of the order of a hundred million billion billion watts. Quite a lot more than a light bulb in your house! Astronomers use the symbol $L_\odot$ to denote the luminosity of the Sun. And then, when we wish to speak about the luminosity of another star, we don't give that in watts, but as a multiple of the luminosity of the Sun. Twice the luminosity of the Sun, or ten times, or half, for instance. The luminosity of the star Sirius is thus $25L_\odot$.

It turns out that the Sun is more luminous than 90% of the stars in the Galaxy. Of the 140 nearest stars, only 6 have $L > L_\odot$, while 119 have $L < 0.1L_\odot$ (less than one tenth the luminosity of the Sun), and 102 have $L < 0.01L_\odot$ (less than one hundredth the luminosity of the Sun). A star with a mass less than a tenth the mass of the Sun is called a *brown dwarf*. When the mass falls between a tenth and a half of the mass of the Sun, it is called a *red dwarf*. They cannot be seen with the naked eye, they have such low luminosity. The first red dwarf was observed in 1917, with a telescope, of course, and the first brown dwarf in 1995! Note that the brown dwarfs are less luminous than the red dwarfs because of their lower mass. We shall see in a moment why such low mass stars also have such low luminosity.

Stars have different masses. Naturally, this mass can vary during the lifetime of the star, but there is also a starting mass, the mass with which the star begins its life. This raises a question: how does a star actually form? To answer this, let's go back to the Big Bang and the formation of the first stars.

The Big Bang predicts an initial production, at the beginning of time, of 75% H and 25% He in terms of mass (the hydrogen atom is less massive than the helium atom, so that actually means a lot more than three hydrogen atoms for every helium atom). However, this matter would not have been distributed perfectly uniformly in space. So imagine a place where the density is slightly higher than in the immediate neighbourhood. This tiny concentration of matter will attract other matter from round about by gravitational attraction. Its density will thus increase, and it will attract still more matter. And so on and so forth. This positive feedback phenomenon is known as gravitational collapse. In some cases, it will clear out a whole region around the original tiny excess concentration.

It should be remembered that matter is *falling* onto the point of higher concentration. This means it is being accelerated by the force of gravity. It will thus fall faster and faster and there will be more and more collisions with matter that has already been accumulated. The matter will become agitated, hence hot! The pressure will also increase under the weight of the falling matter. To put this another way, we are talking about the conversion of gravitational potential energy into the energy of motion, also called kinetic energy, and then into heat. And at some point the conditions may be reached for something to happen that will change forever the future of this star, or let's say, this star in the making. Something that could perhaps put a stop to the collapse, at least for a certain time.

If the temperature reaches 10 or 20 million degrees and the density reaches 100 g/cm^3, about a hundred times the density of water—and this will only be possible if the starting mass of the star to be is high enough—the hydrogen in the core of the star will begin to transform into helium. Here is the reaction:

$$4\mathrm{H} \longrightarrow {}^4\mathrm{He} + \text{energy}\,.$$

It's actually a rather slow reaction, and this is a good thing for us as we shall see in a moment, but it produces energy! Let us take a closer look at the reaction to try to understand what it means. On the left, we have four hydrogen nuclei. (We shall forget the electrons for the moment. They are still in the star, but they can no longer revolve quietly around the nuclei, as they would in an atom, owing to the many collisions between the particles moving around within the star.) So what we have is actually four protons, since the hydrogen nucleus consists solely of one proton. If the situation can provide enough energy and enough pressure, two of these protons may convert into neutrons and the four particles may be forced close enough together to stick to one another by means of the strong force. And this configuration of two protons and two neutrons constitutes a nucleus of helium 4, as we saw not so long ago.

Some energy must be provided to triger this reaction, but once it gets going, it actually delivers energy. Why is that? It happens that the mass of four hydrogen nuclei (four protons) is slightly greater than the mass of a helium 4 nucleus, and the difference of mass Δm is converted into energy according to Einstein's famous formula

$$E = \Delta m\, c^2\ ,$$

where c is the speed of light. That means a lot of energy!

This is what is happening in the core of our own star, the Sun, at this very moment. This is nuclear fusion, and it's already alchemy, because we have transmutation of one element into another, viz., the transmutation of hydrogen into helium. This is also called *nucleosynthesis*, i.e., the synthesis of the nuclei of chemical elements (just as nuclear physics is the study of atomic nuclei). We may say that 'nucleosynthesis' is the modern term for alchemy. A star is effectively a gravitationally confined nuclear reactor, since it is the force of gravity that holds the whole thing together.

The core of the star heats up and this will balance the collapse. Provided that it can continue to produce this nuclear reaction, our Sun will remain in this kind of equilibrium. And this is where we are lucky that the reaction itself proceeds quite slowly. The Sun has already been shining like that for 4.5 billion years, and its luminosity has only increased very slightly, by about 30%, for technical reasons. Moreover, it can continue to burn in the same way for another 4 or 5 billion years.

On the other hand, whenever all the H in the core has burnt, the core will start to collapse once again, because there will be no further source of heat to enable it to resist against the force of gravity. The first law of stellar evolution is that the star will try to make itself as small as possible. Gravity is a truly unforgiving force, as all small children know only too well when learning to walk: gravity is always there, waiting for the slightest mistake, so that it can hurl them to the ground. Nothing can block it and nothing can switch it off! And it's the same for the star. When it can no longer stand up for itself by producing its own heat source, gravity will take over again. The star will contract until the internal pressure becomes great enough to support its whole weight! Because, of course, the internal pressure, and indeed the internal temperature, will increase as the star continues to contract.

Up to now, everything we have said could be applied to any star with sufficient initial mass to trigger the first nuclear reaction. But it is generally true that the life of a star depends to a large extent on that initial mass. In particular, there is a kind of critical mass, about eight times the mass of the Sun, i.e., $8M_\odot$. The life of a star starting out with a mass less than $8M_\odot$, like the Sun, for instance, will be very different from the life of a star with initial mass greater than $8M_\odot$. So let's begin with the first of these cases, then end by discussing what happens to massive stars, which is somewhat more spectacular.

Note to begin with that the stars I referred to as brown dwarfs and red dwarfs start out with too low a mass to ever reach the conditions required to shine in any serious way. But for a star like the Sun or more massive, not only will hydrogen burning occur as described above, but the core will eventually reach a temperature of a hundred million degrees and a density of a hundred thousand g/cm^3 (a hundred thousand times the density of water), and under these conditions, He nuclei can fuse together to form C and O in the core.

The fusion of He into C is shown in Fig. 8. Let us look a little more closely. The carbon nucleus contains 6 protons, otherwise it wouldn't be carbon. In carbon 12, there are also 6 neutrons. So it will take three helium nuclei to build one carbon nucleus, because that makes 3×2 protons and 3×2 neutrons. But

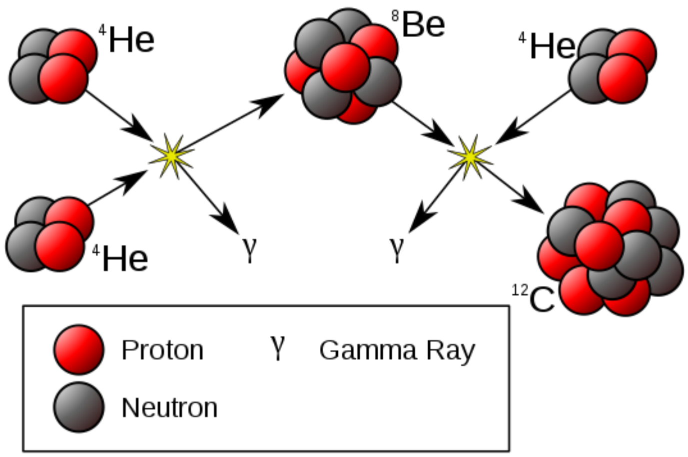


Figure 8: The fusion of He to form C and O at a temperature of a hundred million degrees and a density of a hundred thousand times the density of water. This reaction is also called the triple alpha reaction, since the helium nucleus used to be called an alpha particle, before anyone really knew what it was! Source: en.wikipedia.org/wiki/Triple-alpha_process

there are two problems:

- A considerable force is required to bring so many protons together in the same small space, and this is why the temperature and pressure must be so high.
- The three helium nuclei must collide at almost exactly the same time. Why is this? The collision of two helium nuclei gives a nucleus with 4 protons and 4 neutrons. This is beryllium 8. But the problem with ^{8}Be is that it is highly unstable. This nucleus will decay spontaneously after on average only a tenth of a millionth of a billionth of a second. That's not very long! So the third helium nucleus has to get there *fast*!

The possibility of such a reaction actually happening, and the details of how it happens, thus raised quite a few problems for scientists working on nucleosynthesis in the 1950s, and it was Fred Hoyle, an astrophysicist from Yorkshire, working in Cambridge, who came up with the solution (see Fig. 9).

Fred Hoyle also worked on cosmology. This is the study of the Universe as a whole. And it was him who gave the name 'Big Bang' to our preferred cosmological theory, although actually to make fun of it, because he never really liked the idea that the Universe should be so asymmetrical in time. With two other astronomers, Thomas Gold and Hermann Bondi, he had put forward the so-called *steady state theory*, according to which the Universe was always the same at any time one cared to look, despite the fact that it was expanding. For this to work, matter had to be created everywhere at all times. Given the

Figure 9: Fred Hoyle, the man who solved the problem of carbon production by fusion of helium. He was also famous for other reasons (see text). Source: www.amazon.com/-/es/dp/B00TO7LMUW

prestige of its inventors, this theory was taken seriously, but ended up being falsified by observation. For example, it cannot explain the cosmic background radiation, which fills the Universe and which has existed since very early on after the Big Bang, although gradually cooling.

So why does the name Big Bang poke fun at our preferred theory? Because it makes one think of an explosion, and an explosion is something that occurs in space and in time. But at the beginning of our Universe, there was neither space nor time. Indeed, space–time was created at this instant. As pointed out by Saint Augustin, the Universe was not created *in* space and time, but *with* space and time. And that is actually what our preferred cosmological theory is telling us.

But let's get back to the star we were considering. I said that helium could also fuse into oxygen at this stage, given that the temperature and pressure are now sufficient. Look again at Fig. 8. On the right, there is a nucleus of carbon 12 with its 6 protons and 6 neutrons. If it is joined by another helium nucleus, that will give a nucleus with 8 protons and 8 neutrons, which is oxygen 16. And carbon 12 is highly stable, so it has plenty of time to await the arrival of a fourth helium nucleus.

So what do we have now? After a certain time, starting in the middle of the star and working outwards towards its surface:

- A dense C/O core.
- A first layer around this in which C and He fuse to form O.
- A second layer around the first in which He transforms to C.
- An outer layer in which H is still being transformed into He.

It's a bit like an onion! But why are there these layers? In fact, as we move further away from the center, the temperature and pressure decrease and so we find the previous reactions which didn't require such extreme conditions.

Meanwhile, the whole envelope of the star further from the center than the outermost layer mentioned above, where the temperature and pressure have never been high enough to trigger a nuclear reaction, is blasted by the stellar wind, that is, a persistent flow of high energy particles produced by the nuclear reactions within. This stellar wind contains photons, which are particles of light, but notably also free neutrons (which will be important soon) and other particles. The envelope is thus pushed far away from the star, which swells up to an enormous size! At the same time, the outer surface of the star cools somewhat, becoming redder. The star becomes a *red giant*.

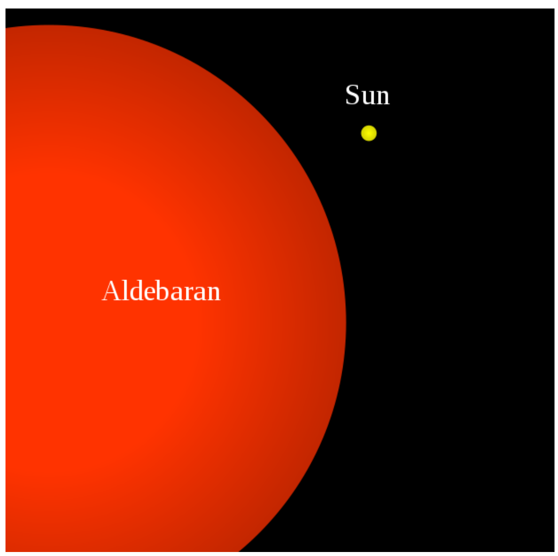


Figure 10: The red giant Aldebaran in the constellation Taurus, compared with the Sun. But note that, one day, our own Sun will grow to be as big as this! Source: en.wikipedia.org/wiki/Aldebaran_in_fiction

Figure 10 shows a red giant for comparison with the size of the Sun. However, our own star will one day swell to this size when it too becomes a red giant in 4 or 5 billion years. To begin with, it will swallow up the orbit of the first planet in our Solar System, which is Mercury. It will continue to swell until it also swallows up the orbit of the second planet, Venus. And then .... But we shouldn't worry. It won't happen for a few billion years. The star shown for comparison here is Aldebaran. It can be seen in the constellation Taurus, not far from Orion. This star is easy to spot. It's rather bright and a reddish colour.

Red giants don't live very long. In the case of the Sun, this stage will only last for about 100 million years. At some point, all the He in the central part of the star will have burnt. The core will then be composed mainly of C and O. The core will thus begin to collapse again, under the relentless force of gravity. When the radius of the core gets down to just 20 000 km, which is about 3% of the present radius of the Sun and about three times the radius of the Earth, an effect known as *quantum degeneracy pressure* will stop the collapse.

I shall give a superficial explanation of this quantum pressure in a moment. I just wanted to mention that it's here that there is a big difference with the life of massive stars ($> 8M_\odot$). We shall discuss this shortly, but the main point is that the collapse of a massive star is much faster and can produce temperatures and pressures high enough to trigger further nuclear reactions in the core. For less massive stars like the Sun, with masses less than $8M_\odot$, there can be no further direct nuclear fusion reactions of the kind described so far.

So what is this quantum degeneracy pressure? Earlier I mentioned that the electrons in the atoms that make up the star would no longer be able to revolve around their original nuclei, given the extreme conditions of temperature and pressure. However, they are still present in the core of the star. They will be moving around at high speeds between the nuclei in what is known as a plasma. And these particles are subject to the *principle of exclusion* first formulated by Wolfgang Pauli, an Austrian physicist who made considerable contributions to the early formulation of quantum theory. This principle says that two such particles cannot be in the same quantum state. Effectively, in the present situation, where the collapse tends to force the electrons ever more closely together, there comes a point where they are compelled to fight back. This is the origin of the quantum pressure which opposes collapse. And the core of the star in this state of quantum degeneracy is what is known as a *white dwarf*.

Meanwhile, the whole of the star's envelope will have been swept far away from this carbon/oxygen core, the white dwarf. The result is a nebula. Two examples are shown in Fig. 11. These nebulas play a crucial role in enriching the Universe with heavier elements. The primordial hydrogen has been transformed, at least in part, into He, C, and O and these new elements are then, at least in part, expelled into the interstellar medium. Moreover, the stellar wind bombards all this matter with free neutrons, and the nuclei in the envelope can capture these neutrons and thereby form even heavier nuclei. So this is another source of alchemy, the production of new elements. I will return to this point below, after describing the life of a massive star.

Before we end this discussion of stars like our own, a thought for the white dwarf. What does the future hold in store for it? In fact, it is condemned to gradually radiate away all its remaining energy and simply fade out of sight.

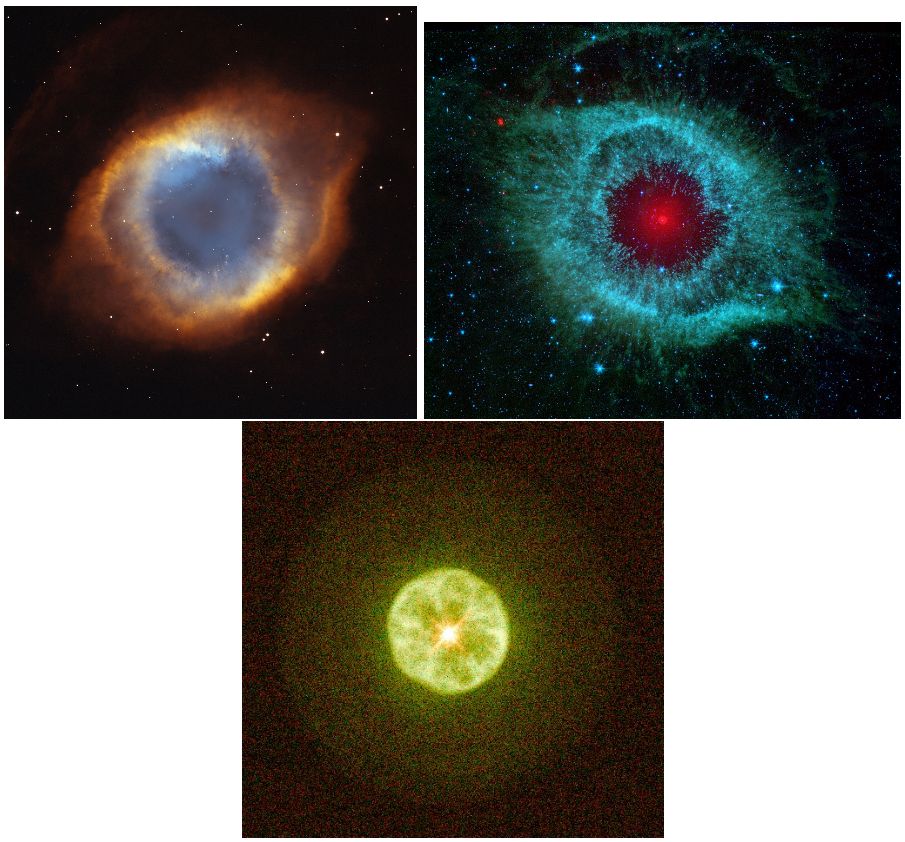


Figure 11: *Upper*: Two views of NGC 7293, the Helix Nebula, located in the constellation of Aquarius. This is known as a planetary nebula, although the word ‘planetary’ is inappropriate here, being just a leftover from the days when we didn’t know what these objects were. This nebula is nicknamed the Eye of God! On the left is a view combining an image taken by the Hubble Space Telescope and the Kitt Peak Observatory in Arizona. On the right, an image taken in the infrared by the Spitzer Space Telescope. Source: fr.wikipedia.org/wiki/Nébuleuse_planétaire. *Lower*: The nebula IC 3568, also known as the Lemon Slice Nebula, in the constellation of Camelopardalis. Source: fr.wikipedia.org/wiki/IC_3568. In both nebulas, the white dwarf is a tiny point of light at the center

For there is no further source of energy within it. All it can do is to cool off, slowly but surely.

And now, the massive stars. What happens when the initial mass exceeds $8M_\odot$? In fact, things happen exactly as before, but much, much more quickly! This is easy enough to understand. There is more matter to fall and more matter to attract, so with a much greater gravitational force. As a consequence, there will be more acceleration in the fall. To put this another way, we are talking about the conversion of gravitational potential energy into energy of movement, or kinetic energy, and then into heat, and there is much more gravitational energy here. For a star that sets out on life with a mass of $20M_\odot$, the hydrogen in the core will be transformed into helium in just ten million years. Compare this with ten *billion* years for the Sun! The helium in the core will be transformed into carbon and oxygen in just a million years. Compare with a *hundred* million years for the Sun!

So once again, we end up with a C/O core, surrounded by a layer in which He $\to$ C, surrounded by a layer in which H $\to$ He, exactly as before. The core now begins to collapse. However, a massive star burns at such high temperature that it reaches conditions in which carbon can engage in nuclear fusion before the core becomes degenerate, i.e., before its collapse is stopped by the quantum degeneracy pressure of the electrons. Indeed, when we reach six hundred million degrees, other nuclear fusion reactions can take place. Here they are:

$$^{12}\mathrm{C} + {}^{12}\mathrm{C} \longrightarrow {}^{20}\mathrm{Ne} + \alpha \ ,$$

$$^{16}\mathrm{O} + {}^{16}\mathrm{O} \longrightarrow {}^{28}\mathrm{Si} + \alpha \ ,$$

where α is an abbreviation for the helium 4 nucleus. In the first reaction, two carbon nuclei combine to give a neon nucleus. Neon is the fluorescent gas used in lighting strips. That's already an interesting piece of alchemy! We take coal and produce a fluorescent gas. In the second reaction, two oxygen nuclei combine to give a silicon nucleus. Silicon is the main ingredient of sand. It's as though we took the air we breathe and made sand from it!

The first reaction is already over after just 300 years. In other words, there's no more carbon in the core. And the second? After just 200 days, there's no more oxygen in the core. Everything starts going faster and faster and at each stage less and less energy is produced to hold the core up against the weight of the surrounding stellar material. This is effectively because the products of the fusion reactions are more and more stable. Collapse continues with other nuclear reactions until finally we arrive at the most stable nucleus. This is iron ^{56}Fe, with 26 protons and 30 neutrons in its nucleus. At a thousand billion degrees and a million times the density of water, we may witness the reaction

$$^{28}\mathrm{Si} + {}^{28}\mathrm{Si} \longrightarrow {}^{56}\mathrm{Fe} \ .$$

And this process is over in just two days!

So what do we have now in our star? Well, it has become rather like an onion (see Fig. 12). At the center, the central part of the core is composed of

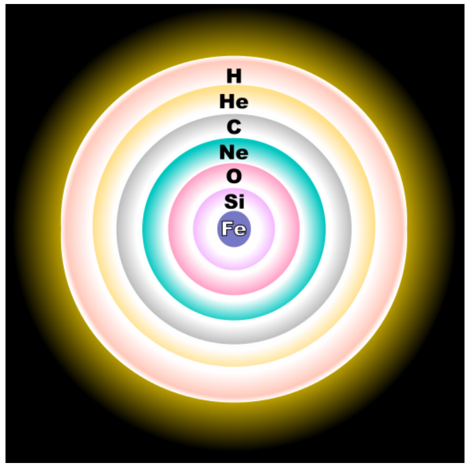


Figure 12: A massive star at the moment when the core has been completely transformed into iron. Source: en.wikipedia.org/wiki/Stellar_evolution

iron. Around it is a layer in which silicon is still being transmuted into iron (which means that the iron core is getting more and more massive). Around that is another layer where the temperature and pressure are slightly lower and oxygen is still being transmuted into silicon. And so on and so forth until we reach a final layer of nuclear fusion in which hydrogen is still being transmuted into helium. As for the less massive stars considered earlier, all this nuclear activity produces a tremendous stellar wind which blasts the outer envelope of the star out to ever greater distances.

But what is really important here is that direct fusion reactions of the kind so far discussed cannot go any further, despite the existence of dozens of elements beyond iron in the periodic table. This is because that would require energy but without being able to return any energy at the end, due to the fact that iron is more stable than all the heavier elements. The iron core thus begins to collapse, and at a tremendous rate. The central part of it soon reaches the degenerate state, supported by the degenerate electron pressure, the quantum effect mentioned earlier. The electrons refuse to be forced any closer together, due to the Pauli exclusion principle. This blocks any further collapse of the core. But more and more iron is being piled onto the iron core from the next layer of the onion in which silicon is transmuting into iron.

And this is where Subrahmanyan Chandrasekhar arrives in a boat from India (see Fig. 13), on his way to study astrophysics in Cambridge. One of his first successes was to calculate the maximal mass of an iron core in the degenerate quantum state. Some say he actually did the calculation while he was on the boat. Well, in those days people had time for things like that! He was not actually the first to do this calculation, but he did it more carefully, taking into account more factors, and he found a value of 1.44 times the mass of the Sun.

Figure 13: Subrahmanyan Chandrasekhar (1910–1995) was an Indian mathematician and astrophysicist. He won the Nobel Prize in Physics in 1983 for his work on the structure and evolution of stars. Source: www.sciencesetavenir.fr/espace/univers/un-doodle-en-hommage-au-physicien-subrahmanyan-chandrasekhar_117526

And of course he used much knowledge already accumulated by others. Science is always a collective effort, even if we tend only to remember certain names!

So let's get back to our star. When the degenerate part reaches a mass of 1.44 times the mass of the Sun—the so-called Chandrasekhar limit—the electron degenerate pressure is no longer sufficient to stop collapse, and it starts to collapse even faster than ever before. In a fraction of a second, it collapses from the size of the planet Mars to become a sphere of diameter 10 km. The iron nuclei are instantaneously destroyed. So what does this leave? A neutron star of mass $1,44M_\odot$. Indeed, this sphere contains only neutrons, following an almost instantaneous process of photodisintegration induced by very high energy gamma rays:

$$^{56}\mathrm{Fe} \longrightarrow 14\,^4\mathrm{He}\ ,$$

$$^4\mathrm{He} + \gamma \longrightarrow 2\mathrm{p} + 2\mathrm{n}\ ,$$

$$\mathrm{p} + \mathrm{e} \longrightarrow \mathrm{n} + \nu\ .$$

The details are not important here. The reactions are only shown to give some idea of what is going on here. In the last reaction, the protons and electrons combine to produce neutrons and neutrinos (ν), the latter being tiny electrically neutral particles with almost no mass. The neutrinos are a story unto themselves! So this new object, the neutron star, is *very* dense. It is said that a teaspoonful of its matter would weigh a billion tonnes. Not the kind of thing you'd put in your tea!

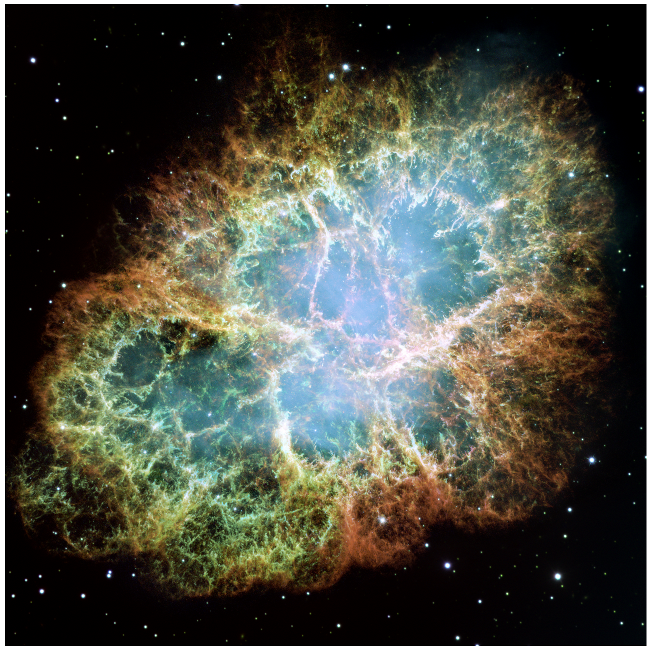


Figure 14: The Crab Nebula. Source: en.wikipedia.org/wiki/Crab_Nebula

So why does this ball of neutrons not just go on collapsing? What could be stopping the collapse so suddenly in this particular state? Once again, the matter reaches a degenerate state due to the quantum effect mentioned above. But this time it's the neutrons and not the electrons that put an end to the show! After all, there are only neutrons, and neutrons like electrons are subject to the Pauli exclusion principle.[3]

But let's not forget the rest of the star, which has been left hanging there in empty space, so to speak, now that the core has instantaneously reduced to almost nothing. Naturally, the rest of the star is already in free fall, and when it arrives on the neutron star that has just formed, it is easy to imagine the consequences, because this object is very dense and as hard as . . . well, a neutron star! All this matter which suddenly lands on it will simply bounce off it, and at very great speed. This is a supernova!

Figure 14 shows what that leads to. This is the example of the Crab Nebula, also called SN 1054, at a distance of 6523 light-years. In other words, what we see in this image is already 6523 years old. But the supernova in question was actually observed by Chinese astronomers in 1054. So what we see here is indeed the result of a supernova almost a thousand years later on! We see that the matter from the star—that is, all the layers of nuclear reactions and the

[3] If the collapsing iron core is too massive, even the neutron degenerate pressure won't stop the collapse and the result will be a black hole.

whole envelope of the star in which there never were any nuclear reactions—has been blasted out into space far away from the tiny neutron star at the center, which is too small to be seen here.

As in the case of the so-called planetary nebulas, what is happening here plays a crucial role in enriching our Universe. Primordial hydrogen has been transformed into heavier elements and these new elements have been expelled into interstellar space. Moreover, in this case, the flow of high energy particles produced by the supernova bombards all this matter with huge amounts of free neutrons, and the nuclei in the envelope of the star can capture these neutrons to form heavier nuclei, as explained above. This process of *neutron capture* is another source of heavy elements, and indeed a very important one.

Meanwhile, practically all the iron produced in the core of our massive star has been destroyed! So how is it that there is any iron in the Universe? It is thought today that most iron is produced in another kind of supernova, but that's another story. As we have seen, direct fusion can produce C, N, O, Ne, Mg, Si, S, Ar, Ca, Ti, Cr, and Fe, and these elements constitute almost the whole mass of the Earth ($> 96\%$). However, we do find heavier elements on Earth and elsewhere in the Universe. The preferred hypothesis today is indeed the above-mentioned neutron capture. We still have a lot to learn about this and much research is being done. In his book, *Stellar Alchemy*, the French astrophysicist Michel Cassé claims that one can make a gold nucleus from an iron nucleus by bombarding it with 141 neutrons, provided that all the neutrons arrive in quick succession, because even a delay of one ten thousandth of a second between the arrivals of the neutrons would be long enough for the highly unstable intermediate nuclei to spontaneously break apart.

It's a surprising recipe that hardly seems probable. But at the same time, gold is extremely rare, isn't it? On Earth, there are roughly 4 g of gold for every 1000 tonnes of rock! However, we have just discovered a situation in which there are vast quantities of neutrons and what is more, we can observe the production of equally vast quantities of gold as it is happening! In 2017 and again in 2019, our *gravitational wave detectors* observed two collisions between neutron stars.[4] And now that you know what a neutron star is—effectively a ball neutrons—you will understand that following such a collision, there will be neutrons all over the place, providing perfect conditions to produce heavy elements like gold, or indeed platinum. When we look at the site of one of these collisions with 'normal' telescopes detecting ordinary electromagnetic waves (light!), we do indeed recognise the signature or 'fingerprint' of gold and platinum (the result of spectroscopic research by people like Bunsen and Kirchhoff, mentioned earlier).[5]

Note that, in order to cover so much material and give an overview with enough detail to understand the main ideas, I have greatly simplified many aspects of stellar nucleosynthesis. Moreover, this is still an active field of research and many things remain to be worked out or observed to corroborate the the-

[4] www.space.com/neutron-star-crash-made-gold-uranium.html

[5] An excellent link discussing what elements are synthesised where, and how they might be synthesised, is `en.wikipedia.org/wiki/S-process`, although it is nominally about the slow neutron capture process.

ory. However, this great discovery is clear: the chemical elements were either created in the Big Bang or synthesised in stars later on. And at least you now know how to produce gold in vast amounts. Of course, you need access to two neutron stars. If the alchemists had known this, they might well have turned to other activities.

Don't hesitate to contact me on `stephen.lyle@trinity.cantab.net` if you have comments or questions.