# Stars

### Introduction

Fascinating and gigantic balls of incandescent gas suspended in an empty space, that shine with their own light. We all know the stars. Even in the sky over our cities, so greatly penalized by light pollution, we are able to see some. At times we are even able to identify some depending on the difference in colour and intensity.
Did you know that we are made of stardust? The iron in our blood, the oxygen that we breathe, the calcium in our bones, all the atoms we are made of, were created in the stars billions of years ago, just like all the other elements that are present on our planet.

## Beyond solar system

### Spheres of incandescent gas

Everybody knows the stars. Even in the skies above our cities, where there is so much light interference from other sources, we can spot some of them. And probably we are able to distinguish them by their color and brightness. In fact there are many kinds of stars and in order to include them all in a single category, something must be said about their intrinsic proprieties.
Stars are gigantic balls of incandescent gas suspended that have their own light. This is not exactly the definition we will find on any Italian vocabulary, but probably it helps us to focus on the real nature of these small bright spots that have always fascinated human beings.
As we said stars are gigantic spheres of incandescent gasses.
In fact all stars are spheroid or semispheric because of gravity forces. All matter found in the universe generates a force of attraction simply because of its mass. If the distribution of matter is uniform, such as for example in a cloud of gas, around the gravity center the mass tends to accumulate in an identical way from every direction, thus forming spheroid shaped celestial bodies. However, because gravity is a weak force, we only see its effects when masses are very large. This is why stars have very large masses. The sun's diameter is 1,4 million km long, 100 times more than the earth's. But the sun is an average star. Star diameters range from a few hundredths to hundreds of times the solar one.
Yet even star dimensions, no matter how large, are small compared to the distances between them. Proxima Centauri, the closest star to our Solar System, is 250 thousand times farther from Earth than the sun. Even at a speed of 300 thousand kilometers per second, Proxima's light takes four years to reach us.
Now we know that stars are enormous spheres scatterred in the empty parts of interstellar space. What are they made of? We haven't spoken yet about their composition. Stars are made of high temperature gasses. Even though there are many kinds of stars, by analyzing the light that they emit, we know that they are composed mainly of hydrogen (70%) and helium (less than 30%), the most simple and abundant substances in the Universe, in addition to minimal percentages of more complex elements such as, for instance, carbon, oxygen, nitrogen and metal.
Stellar gas has a very high temperature. The sun's surface is around 6000 degrees, but some stars can be almost ten times hotter. All bodies surrounded by a cooler environment tend to release their inner energy irradiating it in the form of light and heat. This is why stars emit light; the hotter they are the brighter they shine. The power released by the sun as light and heat is equal to ten thousand billion atomic bombs the size of the one dropped on Nagasaki. And there are stars that are one million times brighter than the sun!
But this is not all. Stars have colors. For instance, if you observe Orion's big constellation on a winter night, you can notice the left shoulder of the hunter is distinctly red, while the right foot is definitely blue. A star's color gives astronomers precious information on the energy with which most of its radiation is released. Since the way that a star emits light depends solely on its surface temperature, thus color becomes and indicator of its temperature. Hotter stars whose surface can reach 40 thousand degrees emit a blue light, while the coldest ones, reaching "only" 2000 – 3000 degrees release red radiation. The sun at 6000 degrees is yellow. Therefore we have proceed to create a star

classification based on this characteristic which includes all the main groups  O, B, A, F, G, K, M from the hotter to the colder ones.

## Spheres suspended

Let's go back to the initial definition that we have given of a star.
First of all let us stop and think: have we ever seen a gas take on a definite shape, such as a sphere, without beong enclosed in a container? The answer obviously is no, because gasses tend to spread and occupy all the available space. Then how can it be that the gasses of the stars are somehow confined and don't dispel into space? The explanation can be found once again in gas behavior: when compressed, a gas warms becomes warmer. Stars have  a hydrostatic equilibrium thanks to the balance between two equal forces pulling in opposite directions: gravity, that tends to make matter collapse inwards toward the center, and pressure caused by the expansion of the hot gas, pulling outwards Astronomers estimate that temperatures at the center of the sun reach 15 million degrees Celsius and that density is about a dozen times the one of lead. Nevertheless the center of the sun is still gaseous because gas at such high temperatures is in a particular state called plasma where electrons and nuclei, are no longer bound by their classical atomic structure so they generate clouds of free-floating electrically charged particles; in this state, matter is highly compressible thus remaining in a gaseous state.
This eternal clash between forces lasts throughout the star's long life. Star longevity has been one of the main problems for astrophysics to solve in the past. Stars in fact appear eternal and immutable compared to our life time. Let's take the sun for instance: because Earth cannot exist without its star , we know that the sun is at least as old as our Planet which is about 4,5 billion years old. And this is not all: terrestrial fossil discoveries let us know that during all this time, the sun has continued to shine more or less as it does nowadays. The age problem is strictly related to the production system of the energy released. In fact, this energy could come solely from gravity: as the sun contracts it heats up and becomes brighter. Estimates on the gravitational energy available to fuel the process prove, however, that the sun cannot survive beyond thirty million years. Therefore there must be an alternative energy source to fuel the longevity that we have observed.

## Spheres that shine

To discover the system which is able to heat so much gas and for such a long time we have to dive into the microscopic world of atomic nuclei. Atoms have a precise structure: they have a nucleus formed by particles called protons and neutrons, around which orbits a cloud of smaller particles called electrons. We are in the extremely small world: take a millimeter, divide it by a million and then again by ten and we will have the size of an atom. Generally atoms are stable, but particular pressure, density and temperature conditions, can cause a reaction which will transform the atoms of a certain element into atoms of another element. Any alchemist's dream!
The core of a star is a gigantic nuclear reactor where simple atoms melt and create more complex atoms. Most of a star's existence is sustained by the fusion of hydrogen nuclei into helium nuclei. The energy produced by the reaction heats the gas which expands, thus opposing gravitational collapse, and then reaches the surface from where it scatters in space in the form of light and heat. Right at this very moment within the sun's core 4 million tons of hydrogen are being burned per second; this impressing rhythm has remained the same for the past 5 billion years and will remain unchanged for the another 5.
When the main gas heating fuel runs out, the precious balance between forces that keep a star alive are lost.  In the difficult search for a new stability, the star evolves, beginning fusion processes of heavier elements, such as carbon. Then, from the core of a star like the sun, the enormous quantity of energy produced rises to the surface over millions of years. As it travels through thick layers of dense gas, this radiation interacts with gas atoms along the way and is degraded, somewhat like what happens to the kinetic energy in a billiard ball when it collides with another one. On its way, this energy will also pass through a turbulent gas layer where gas columns, rather like huge escalators, carry it up to the surface where it is released into space where it will travel until it reaches us.

## Star groups: reality or fiction?

Constellations are groups of stars which form certain familiar shapes in the sky. Nevertheless, the celestial sphere is simply a two-dimensional projection of the universe that surrounds us centred on our planet. Thus when considering the third dimension, which is depth, stars belonging to the same constellation are not bound together in any way, in fact, they are often considerably far from one another. Therefore the belief that certain constellations may influence people's lives is apparently groundless.

Yet this doesn't mean that stars live alone, on the contrary. Often stars form complex systems with two, three or more components bound together by their mutual gravitational attraction.

The most common configuration are double stars, which are pairs of stars that orbit around a single centre of gravity. In particularly tight systems, the two components can exchange masses, sometimes consistently. In fact, the gravitation force of the most dense and compact star draws in matter from the more expanded mate, even if their masses should be the same size.

In addition to doubles, one can find multiple systems and real masses, groups of stars bound together by gravity. The latter are divided into two families: open masses and globular ones. The first ones are made up by a number of newly formed stars ranging from ten to a thousand and are all gathered in an area with an approximately ten light year diameter. The open masses are in fact proof of the stars' young age because they tend to be born in clusters within our galaxy's disk. Within scale times of two to three billion years open masses will break up: gravitational interactions act as slingshots and end up expelling all the massed stars. Numerous open masses are sufficiently close for us to see them with the naked eye: the brightest one of them all is the one of the Seven Sisters in the Taurus constellation, only 425 light years away from Earth.

Globular masses instead are totally different. They are more unusual than the open ones, they can be made up of over a million of stars gathered in no more than about one hundred light years: they are so dense that they can survive much longer against gravitation attacks which instead break up all the young open masses. In fact globular masses are made of very old stars, that were born when the galaxy was still being formed, and they are spread in a spherical halo around the centre. Scientists study them just because they can foster secrets on the formation of the Milky Way itself.

## The distance problem

One of the principal problems in astronomy is the measurement of stellar distance. We have already seen that all objects are "squashed" on a spherical projection, known as celestial sphere, at the centre of which we have Earth. A lack of depth obviously brings to  misled calculations of luminosity and distances among the objects. The sun for instance is a medium sized object, yet because it is also the star which is closer to us, it seems larger and brighter than many other stars that, even if they are much brighter, they seem smaller and weaker because of the distance.

There are many ways to calculate the distance between the stars; one of these goes by the yearly parallax. The parallax is the apparent movement of an object compared to its background, when looked at from two different points. The farther an object is, the smaller and less noticeable its movement will be when increasing the distance between the two points of observation. Since the stars are so distant, in order to be able to notice the parallax, they are watched every six months, that is when Earth is at two opposite ends of its orbit around the sun. Thus the yearly parallax method. By measuring the angle of this movement and knowing the radius of earth's orbit, we can calculate the distance between us and the object with a simple trigonometry formula: D = Rearth : tgangle expressed in parsec. Parsec is the unit of measurement used by astronomers for distances in the Universe; the name stands for the abbreviation of  "second parallax" which is the distance from which one can see the radius of earth's orbit under an angle of 1 arcsecond. 1 parsec is the equivalent of 3.26 light years. In the past years we have been able to calculate with remarkable accuracy the distance of most of the closest stars with the parallax method thanks to the Hypparcos satellite.

Nevertheless one is easily inclined to think that the validity of this method is limited to stars near us; in the case of very distant stars the parallax angle becomes so small that it cannot be measured so we have to turn to indirect measuring methods. For instance, one can take into consideration some variable stars, whose variability is linked to their intrinsic luminosity. By measuring their apparent luminosity, meaning the one that we measure from Earth, it is possible to

calculate their distance.
Several objects belong to this class of candle samples, the best known are the Cepheid, luminous stars that can be seen also in other galaxies beyond the Milky Way. The measuring precision of these stars allowed the Astronomer Edwin Hubble to measure the distance of the closest galaxies and discover their recession, paving the way to modern cosmology and the Big Bang theory. Today we are able to evaluate, even if not with perfect accuracy, galactic distances of hundreds of millions, and even billions, of light years.

# Life of a star

## Star evolution

Stars are born, live and die like living beings; the only difference is that they do it in such a large time frame as to appear eternal and immutable. Therefore, if we want to study their lifecycle the only thing that we can do is to assume that all stars have a similar evolutionary process and pick a vast number of samples at different stages of their life span. Rather like observing a newborn, an adult and an old person to study man's cycle.
Why do stars evolve? All life long a star has to put up with a titanic battle between the two main forces that govern it. If some conditions are modified and one prevails over the other the balance is lost, triggering chain reactions that modify the structure of the star leading to a new balance. Therefore, the evolution of a star will go through long stable phases alternated by short periods of instability when main evolutionary changes occur. Development of a star depends above all on its mass. The greater the amount of matter , the greater the amount of pressure necessary to oppose the collapse and therefore the greater the amount of fuel burned. Consequently, larger stars are brighter than the ones with a smaller mass, but they also live much less.

## Birth and maturity

Where are stars born? Interstellar space isn't empty but is full of so called interstellar medium, a widespread evenly distributed gas and dust mix. Yet if we observe it on a reduced scale we notice that the matter tends to thicken and form gas clouds, for the most part hydrogen, and dust. These clouds have a dynamic and thermal balance at the extreme temperature of -270°C. For reasons beyond the clouds themselves, sometimes the substances they are made of will start to compress into a smaller volume and be affected by the mutual gravitational attraction. As the gas contracts, compression heats up the gas particularly in the inner parts of the cloud and as the body forms it begins to shine. But it is only when the inner temperature reaches 10 million degrees thus triggering the first nuclear reactions that a star is actually born. In fact the heat generated by hydrogen fusion makes the gas expand which in turn, effectively counterbalances the gravitational collapse over an extremely long period of time. This is when the new star finds the most stable and longer lasting balance period of its whole existence, which allows it to be more or less constant in size and brightness. Our sun is approximately half way through that phase; in stars with a similar mass this period lasts about 10 billion years.
As we said, the sun is a medium sized star. Most of the stars in the Milky Way are smaller than ours and are called red dwarfs; with a mass equal to one third of our star, they burn their fuel at a much slower rate and can stay at this developing stage even for hundreds of billions of years, a longer time than that of the entire universe.
Below 0,08 solar masses there are the brown dwarfs, bodies that cannot actually be considered stars because the gravitational collapse is not strong enough to trigger any inner nuclear reactions.
Some stars, on the contrary, are even larger than the sun. With a mass between 10 and 50 times the solar one and 1000 times larger, we have the so called super giants. Bodies of this size burn fuel at a very high speed and, consequently, have a short life of only a few hundred million years, with frequent phases of instability during which they may suffer substantial mass loss. Super giant stars are generally blue, but throughout their evolution they will change color to ultimately become red.

## Old Age

What happens when the main fuel is running out? The star has burnt almost all the available hydrogen, which accounts for about 10% of the total, in the nuclear fusion, and the nucleus is composed almost exclusively of inert helium. The energy production that counterbalanced the gravitational collapse is no longer sufficient to oppose it and the balance is lost. Even if at first no change is noticeable on the star's surface, the nucleus starts to contract under the pressure of its mass, gradually increasing its density and temperature. The first consequence is that fusion reactions occur out of the nucleus which by now is spent involving the thin layer of surrounding hydrogen. The displacement of fusion reactions towards the outside causes an increase in gas pressure of the superficial regions. As a result, while the nucleus of the star contracts, the external areas expand, cooling off because the same amount of heat is now released from a larger surface. We have already said that a star's color is linked to its surface temperature and that the cooler stars tend to be red.

Therefore, as the star swells it becomes red, and enters a developing phase known as the red giant. Red giants can have diameters ranging from 50 to 2000 times larger than the sun and can be as much as three times cooler than our star.

## Death

And then? It all depends on the mass of the star.

Stars that are smaller than the sun become unstable. As the star is no longer able to manage its entire mass, it expels the superficial layers in a gas puff, thus creating a planetary nebula. There is no planetary nebula the same as another: the expelled gas becomes of many different colors and takes on different shapes, creating one of the most fascinating shows in the sky. The center of the nebula contains the beating heart of the old star which is no larger  than our Planet, but extremely hot: a white dwarf. Nuclear fusion no longer occurs in this type of star; gravity's opponent is no longer the expansion pressure of high temperature gas, but the pressure generated by gas being compressed into a very small volume. On a white dwarf a teaspoonful of matter can weigh as much as a car! In this state the body gradually loses its residual energy, cooling off and gradually fading until it becomes a translucent, dark lifeless body in the cold interstellar space.

In stars with masses comparable to the sun, the nucleus stops collapsing only when the inner temperature reaches above 100 million degrees, the threshold temperature necessary to start up nuclear fusions again. This time helium atoms fuse with carbon atoms releasing the necessary energy to regain the lost balance; however with hydrogen fusion, stability can last tens of billions of years, while the one obtained with helium fusion is not so long lasting and runs out within a billion years. When helium runs out as well, this balance is lost again and the force of gravity takes over. The sun's fate is the same as the red dwarfs', besides helium's brief action, the red giant phase will be followed by  the white dwarf surrounded by planetary nebula one.

However, the destiny of stars with a mass 3 to 4 times larger than the sun's is very different. In these stars the balance is lost rather frequently and at progressively shorter intervals. Each time that fuel for the nuclear reaction runs out, the process that we have just described is repeated over and over but every time the elements involved are heavier thus providing an increasingly shorter period of stability. When a star is left with an iron nucleus, the nuclear fusion reaction ends forever. In the absence of an opposing force, gravity causes the nucleus to collapse suddenly thus releasing stored energy: the star explodes and becomes a supernova, so bright that for a couple of months it will obscure even the galaxy it belongs to. However the explosion does not completely destroy the star; the nucleus survives and, once again, its fate will depend on its mass. In the case of nuclei up to 2 to 3 times the size of the sun, a neutron star will be created, in other words a body which is made exclusively of this type of atomic particles. Here  gravitational collapse is opposed once again by the pressure coming from the matter's extremely high density. Thus, on a neutron star, a teaspoonful of matter can weigh as much as 100 million cars. It is as if the entire solar mass was compressed into a sphere with a ten km radius, just slightly larger than a medium sized city.

Sometimes neutron stars revolve at high speeds around their axis. In this case the body is called a pulsar, because its light is channeled in the direction of its magnetic field, which is 1000 billion times more powerful than earth's. This

phenomenon produces a luminous pulsation, similar to the beam of a light house which we can see only when it shines in our direction. Recently we have discovered the fastest pulsar ever, which rotates at the astonishing speed of about 1100 revolutions per second!
If the star is even more massive, we will be able to witness the ultimate triumph of gravity; in fact, their collapse generates the notorious black holes, which are bodies so dense and compact that not even light is able to escape from their surface. Because the only source of information that we have in astronomy is the one brought to us by light, for decades black holes have been the mere result of theoretical calculations. Their existence has been proven only in the past 50 years and this proof is obtained indirectly from the gravitational effects that they have on their immediate surroundings...

## Compact objects

In the chapter on star evolution we said that both in white dwarfs as well as neutron stars the gravitational collapse is opposed by a pressure which no longer depends on gas temperature, but on its density. In astrophysics bodies of this kind are called compact objects and the matter of which they are made of is called degenerate matter. In order to explain this behaviour we must go from the extremely huge field to the infinitely small one: here is where modern quantum mechanics come to help us. However one must not be surprised by the leap from one scientific discipline to another. The different scientific branches support each other and more and more often their discoveries overlap to give a single more complete picture of the situation. So, quantum mechanics say that atomic particles, such as protons, neutrons and electrons, have a series of proprieties which characterize them: mass, electric charge and certain numbers, called quantum numbers, that describe its energy. This kind of particles obey to a law called Pauli's exclusion principle, from the name of the Austrian physicist who discovered it: two energetically identical particles cannot coexist in very little space.
In a white dwarf, matter is ionized and electrons are free of their atomic orbits around the nuclei.
During gravitational collapse, matter's density increases and so does the electron concentration within a certain space volume. Compression continues  until the electrons are able to assume energetic configurations that distinguish them. When all possible combinations have run out, according to Pauli's exclusion principle no other electrons can enter that given volume; thus a barrier is formed which prevents matter from collapsing any further. Therefore the white dwarf reaches its final stable configuration.
The same mechanism takes place also in neutron stars; during the final collapse the star's elevated mass produces density so that atomic electrons and protons bind together to form neutrons. Thus the star is composed by a compact mass of heavy electrically neutral particles that is imploding under the gravity effect. Once again the quantum proprieties of these particles which, like electrons, are ruled by Pauli's exclusion principle. Therefore, once a certain threshold has been passed, neutron density stops the gravitational collapse, giving the star permanent stability.

## Nuclear reactions

There are two reactions that involve an atom's nucleus: fusion and fission.
The first starts from simple elements to produce complex ones; the second acts in the opposite way by splitting nuclei of heavy elements into nuclei of lighter elements.
In both cases there is a very high energy output. In the case of fusion for instance: the mass of the atomic nuclei that melt is greater than that of the new nucleus that will form. Since we know that mass and energy are equivalent as according to Einstein's famous formula of E=mc2, the difference in mass is what is transformed into energy.
Likewise, also in fission the energy produced comes from the difference between the initial nucleus mass and that of the two resultant nuclei: in this case the first is greater than the sum of the latter.
To produce energy however, not all elements can melt just like not all of them can split. In nature in fact phenomena tend to be drawn spontaneously towards low "effort" states. Therefore if more energy is needed to split a nucleus than to keep it together, fission will not occur. This is the case in lighter elements; by melting and increasing the number of particles, the nucleus becomes more stable and excess energy will be released. On the other hand, if the nucleus of an element becomes too big, it will require a lot of energy to keep it together. Therefore it is easier to split it into two lighter and more

stable nuclei by releasing, once again, the surplus energy.
When does fission become preferable to fusion in terms of energy? The limit is iron; its nucleus is too large to melt again and be able to produce another stable nucleus. Therefore the fusion of two iron nuclei requires more energy than it produces; so from here on the most convenient reaction is nuclear fission. In fact, it is no coincidence that during the evolution of massive stars, once iron is created in the nucleus no further fusions can take place.