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.