Biography of a star

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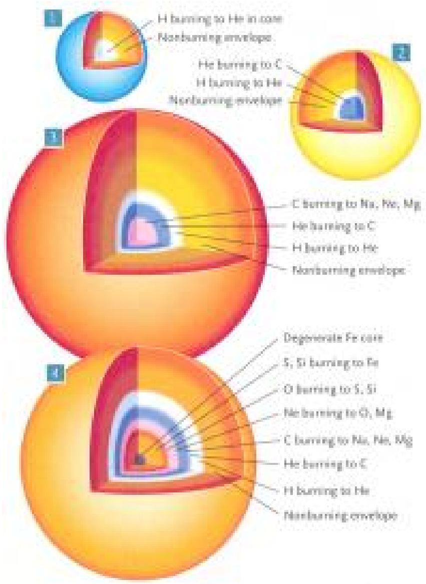
Plasma laboratory in the firmament: Dozens of young stars shine in the NGC 3603 nebula. Today, astrophysicists replay the births and biographies of stars on computers. Credit: NASA, ESA and the Hubble Heritdge (STSci/AURA) - ESA/Hubble Collaboration

Nuclear fusion is a virtually inexhaustible source of energy, and for decades now scientists have been working on exploiting it. A process that continues to present difficulties in laboratories on Earth has been running smoothly in stars like our own Sun for billions of years. But how do the stars work? How are they born? How do they die? Achim Weiss at the Max Planck Institute for Astrophysics in Garching tracks the life cycle of the cosmic plasma spheres - not with a telescope, but by using computer model calculations.

For a glimpse of the world's largest laboratory, you need only look into the clear night sky far from the bright city lights. And if, at the same time, you take a deep breath of fresh country air, you will be supplying your body with the very substances that are produced in this laboratory. Elements such as nitrogen, oxygen and carbon originate in nurseries that have sparkled on the terrestrial firmament since time immemorial: sometimes brighter, sometimes less bright; sometimes white, sometimes in shades of yellow, blue or red.



Stellar element cuisine: From simple hydrogen fusion (1) in the core of a star, the process passes through the various stages of shell burning (2, 3), ending in the creation of heavy elements up to and including iron (4). Credit: S&T: Casey Reed / Source: J. Hester & others

The stars have always fascinated man. As recently as the 1850s, however, researchers were still speculating over the nature of these flickering lights. “We do not know what the stars are, and never will,” one professor is reported to have answered when asked by a young physics student whether there might not perhaps be some way of learning more about the universe than merely the position, distance and brightness of the Sun, moon and stars. The student's name was Karl Friedrich Zöllner, and he was by no means satisfied with his professor's answer. Undeterred, he continued his studies and became one of the first astrophysicists– a profession that he played a part in shaping.

Achim Weiss shares the same profession, and works, appropriately, at the Max Planck Institute for Astrophysics. He has a surprisingly uncomplicated answer to Zöllner's question: "Stars are simple plasma spheres that are subject to their own gravity." A plasma is a gas consisting of ions, electrons and neutral particles; over 99 percent of the visible matter in the universe is in this state. For its part, gravitation is the dominating force in space, acting upon all objects that are substantially larger than molecules. Little else is needed in the way of parts to build a star. Ingredients such as magnetic fields, vibration or electrical phenomena are rarely significant – either in nature or in the computer in Garching on which Weiss models stars.

In space, the birth of a star begins with a giant gas cloud. The mass of this cloud must be so great that gravity prevails against the internal pressure and the turbulence that would drive the filigree structure apart. For its birth to proceed, the star presumably needs a little gentle help from outside, such as the pressure wave of a nearby supernova, that is, an exploded sun (see the box "Furious Finale").

At some point, the cloud breaks up into smaller lumps, each of which collapses. Shackled by gravitation, the particles within such a fragment bunch up. "If this were to continue indefinitely, the star's birth would end in a black hole," says Achim Weiss. How does the inside of the emerging gas sphere withstand the growing gravitational pressure? What stops the stellar embryo from breaking up?

The compressive work of gravity generates heat and pressure. The heat causes the electrons to separate from the cores of their atoms – a plasma is produced. And the pressure enables the gas to build up a "counter-force" against the gravitation: at any given distance from the sphere's center, the pressure is exactly equal to the weight of the gas masses lying above it. The star has become a stable structure. Or as an astrophysicist would put it: it is in a state of hydrostatic equilibrium.

Such a state can be reproduced by a simple experiment: carefully press in a bicycle pump, then block off the outlet with your finger. Since air in the pump is no longer able to flow out, pressure builds up in the tube and prevents the piston from moving. If the right amount of pressure is applied to the piston, it remains stationary in the tube of the pump and a form of equilibrium is produced.

"What happens next in the star's life depends entirely on its mass," says Achim Weiss. The mass is therefore the decisive parameter in the model calculations. In a perfectly normal, average star like our own Sun (mass: 1.989 x 1030 kg), an event with far-reaching consequences occurs after its birth, which lasts a few hundred thousand years. In the center, the gas – primarily hydrogen – heats up to a temperature of over ten million degrees Celsius. At this astronomically high temperature, a fusion reactor ignites, and nucleosynthesis begins: four hydrogen nuclei (protons) combine to form a nucleus of helium-4.

Only now has the cosmic gas sphere become a full member of the star family. The reason is that stars have another property that differentiates them crucially from planets: they shine, because they derive energy from nucleosynthesis. The fusion reactor also ensures that the gas remains hot and delivers sufficient pressure to maintain the hydrostatic equilibrium.

Some stars, however, do not possess sufficient substance at birth. If their mass is less than 75 times that of the planet Jupiter, or in other words less than 8 percent of the mass of the Sun, fusion reactions may still occur on a limited scale within them; a proton, for example, may fuse with deuterium nucleus, consisting of one proton and one neutron, to form a helium-3 nucleus. However, lightweights such as these among the stars never reach the stage of steady hydrogen burning. (The term "burning" is used for historical reasons and is usual in astrophysics; it actually refers to "fusion" and is unrelated to chemical combustion.)

These "black sheep" of the star family are called brown dwarfs. Their lives are fairly unspectacular: owing to their low core temperature, the gas pressure is not sufficient to keep the gas spheres in equilibrium in the long term. Ultimately, gravity gains the upper hand. The brown dwarfs shrink and convert their gravitational energy into heat. Incidentally, this process, known as the Kelvin-Helmholtz contraction, was discussed by astronomers as one of the possible sources of stars' energy, before they solved the riddle in the 20th century with the aid of nuclear fusion.

As the brown dwarfs shrink and cool down, however, the properties of the gases composed of free electrons change: they degenerate, as physicists say. This state has a peculiar feature: the temperature becomes decoupled from the pressure and density, and the star is able to cool down without the pressure dropping. The star remains stabilized, and therefore does not vanish as a small black hole; instead, it becomes progressively colder and darker.

But back to stars of normal weight. A few million years after birth, the young star checks the deluge of matter from its parent cloud by means of increasingly intense radiation and a rising wind of charged particles that it spits off its surface into space. With these mechanisms, the star avoids a further increase in mass and reaches the nuclear fusion phase. At this point, it enters the main sequence in the Hertzsprung-Russell diagram (see the box "Stellar Class Society").

A star might be expected to respect its place in this society forever, according to its initial mass. But this is by no means the case. The population density in the Hertzsprung-Russell diagram (HRD) reflects the relative frequency with which individual star types occur at a particular point in time. If, however, the data from the same stars were to be entered in an HRD every couple hundred thousand years, and the measurements repeated over a period of several billion years, we would notice movement: in the resulting time-lapse movie, some stars would enter the main sequence and remain in it for a long time, only to leave it very quickly toward the giant sequence, finally "crashing" into the dwarfs. In other words, stars are by no means static plasma spheres – they develop. "I am interested in these differences in stars' biographies for my calculations," says Max Planck researcher Weiss.

Let us consider a star of the same type as our Sun. Nuclear fusion functions smoothly only when the external conditions such as pressure, density and temperature are right, and sufficient fuel is also available. At this point, the Sun has consumed about half of the hydrogen at its core by nuclear fusion; around 70 percent of its mass lies within half the solar radius of 350,000 kilometers. Over time, the hydrogen reserves are completely exhausted, and increasing quantities of helium collect at the heart of the Sun until it consists entirely of helium, something that will happen in around six billion years' time. Since the Sun is already four and a half billion years old, it will have had a fairly stable life of ten billion years by that point.

When hydrogen burning at the Sun's center ceases, the star has a problem. It loses energy, but tries to maintain the hydrostatic equilibrium. Fusion in the interior no longer delivers energy. The Sun uses a trick to compensate for this deficit: the core begins to contract, and converts gravitational energy into heat. In the process, it heats up, becoming so hot that the layers outside the burnt-out core reach a sufficiently high temperature to maintain the hydrogen fusion.

Calculations show that this burning of the shell eats its way progressively outward over time. And something is also happening on the inside: the core contracts further still and heats up so much that, ultimately, the helium ignites.

Nuclear fusion takes a detour

At this point, the Sun draws its energy from two sources. Whereas in the shell, the hydrogen is fusing to form helium, the triple-alpha process is taking place in the core: a carbon nucleus is created from each set of three helium nuclei (alpha particles). This takes place in a roundabout way, however. The fusion of two helium nuclei first produces an unstable beryllium nucleus with a half- life of only 10-16 seconds.

Only when, during its extremely brief existence, this helium nucleus collides with another helium nucleus is stable carbon produced. The capture of further helium nuclei may also cause oxygen and neon nuclei to form. In order to ignite the helium, the core contracts, as already mentioned, becoming hotter in the process. At the same time, however, the outer shell greatly expands, causing the surface temperature to fall from values of some 6,000 degrees to around 3,000 degrees Celsius. The Sun has increased its radius a hundredfold, and shines with a reddish light up to 5,000 times as brightly as it does at present: it has become a red giant. Accordingly, it migrates in the Hertzsprung-Russell diagram to the giant sequence.

“Recording such a biography requires numerical programs that describe the star as an ideal gas sphere,” says Achim Weiss. In principle, the task is to divide the star mathematically into “onion skins,” and to determine the chemical composition, physical structure (mass, temperature, density, energy flow) and type of nuclear reaction for each of them. In order for a star to be analyzed for a particular point in time, Weiss and his colleagues typically require a thousand layers. The result is a snapshot of the stellar glass sphere: a model of a star.

In the second step, Weiss then calculates the changes that take place in this model, for example as a result of the nuclear fusion processes, over a given time. He then generates the next, slightly older model. In this way, the researcher tracks the development of a star in the computer. In order to test the calculations in practice, some kind of initial model is first required. For this purpose, Weiss uses the measurable state parameters of an actual, undeveloped star as approximate values – so its mass, luminosity and radius. He then sets these state parameters to zero for the center and begins to calculate in stages from the inside out. “Only once we have found a solution in this way for the initial model do we begin the actual calculations,” says the astrophysicist.

What is the subsequent fate of a star with the mass of our Sun? Achim Weiss solves this time problem by calculating a further model for a point later on in the Sun’s life, for example a million years from now. “Approximately 10,000 individual models are needed in order to describe the entire life of a star,” says Weiss. The time interval between these models must not be too great, however, particularly at an advanced stage in the star’s life: at the giant stage, events follow in quick succession – once the helium in the core has transformed completely into carbon and oxygen. The core is then surrounded by two shells: in the inner shell, helium burns to form carbon; in the outer shell, hydrogen burns to form helium.

In the space of a few tens of thousands of years, a star goes through a wild phase. First, the carbon/oxygen core contracts, while at the same time, the envelope expands. This process does not take place evenly, however, but rather in bursts of greater or lesser regularity during which the star inflates, once again increasing strongly in size and luminosity. During this process, the two outer shells do not burn simultaneously, but alternately.

And an astonishing process takes place within the star: “The complicated interplay of forces creates the conditions for the nucleosynthesis of heavy elements,” explains Achim Weiss, “and violent convection flows are generated within the star.” These flows use particles to transport energy, and thoroughly mix the gas. The heat given off by a radiator is transported in the same way: hot air rises, while cool air falls. You need only hold your hand above a hot radiator to experience this phenomenon for yourself.

The resulting “eddies” in the star cause a certain amount of hydrogen from the outer layer to reach the helium that is burning in the shell beneath it. There, the protons are able to react with the carbon, resulting in neutrons being released. The neutrons are captured by the iron particles that were present in the star in small quantities from the beginning, resulting in the formation of neutron- rich iron isotopes.

If too many neutrons accumulate, radioactive beta decay occurs, which in turn creates stable cobalt nuclei. The neutrons are thus captured progressively by the atomic nuclei, which then become progressively heavier. This “s-process” (s for slow) produces all elements up to and including lead. According to Achim Weiss, “one day, the Sun will produce barium and other rare earths such as lanthanum.”

At any rate, the star’s death is now imminent. In the final phase, it loses several tenths of its mass within the space of a few tens of thousands of years, at the end of which 99 percent of its mass is accounted for by its carbon/oxygen core and only half a percent each by the thin hydrogen envelope and the helium shell. The carbon/oxygen core is effectively blasted clear in much the same way that the desert wind blasts a stone free of sand. The material that is carried off forms an expanding envelope surrounding the star; it is lit by the star, and it assumes the most diverse shapes, such as rings, spheres or asymmetrical structures. In the “hard core,” the fusion processes ultimately grind to a complete halt.

The star's meager remains have a temperature of a few tens of thousands of degrees, and are now only as large as the Earth. The star now appears in the Hertzsprung-Russell diagram as a white dwarf: at first still hot and bright, but in the absence of nuclear fusion, cooling down and becoming dark, first quickly, then more and more slowly – just like the brown dwarfs. When the computer has churned out the state parameters for such a white dwarf – endless columns of figures for values such as the density, radius, mass and temperature – Weiss' work is normally over; a white dwarf is the final stage of a star of low or medium mass.

Life for the heavyweights is faster and more dramatic: while a star such as the Sun remains on the main sequence of the Hertzsprung-Russell diagram for 10 billion years, a star with ten times its mass stays there for only 20 million years. It is much more wasteful of its fuel reserves, and ultimately fuses elements in its core up to and including iron. Should it experience an energy crisis, it bursts. At the Max Planck Institute for Astrophysics, a dedicated research group is studying the simulation of supernovae of this kind (see the box "Furious Finale").

What connection exists between a white dwarf and the star from which it developed? This is one of the problems that Achim Weiss is studying with the aid of his models. For this purpose, the researcher obtains from catalogs the data of suns belonging to a cluster. Clusters are collections of several hundreds or thousands of suns that were born almost simultaneously many millions of years ago. Since they were not all endowed with the same mass at birth, their lives have taken different paths. Their ages can be determined from the "population density" at various points in the Hertzsprung- Russell diagram.

Let us assume that a cluster is 500 million years old, and that Weiss finds within it a white dwarf with a cooling age of 100 million years. The cooling age is the time that has elapsed since the star developed into a white dwarf. In this example, this means that the star had previously lived normally for 400 million years. “The problem to be solved now, says Weiss, is: What star takes 400 million years to develop into a white dwarf?” In this case, it could be a star with approximately three solar masses. Using his models, the researcher examines this “initial final mass relationship” and obtains results that are sometimes confusing.

All stars with the same initial mass would normally be assumed to have the same final mass as well. As an example, however, the final masses of the white dwarfs in the Beehive Cluster differ by a factor of two. “I have no idea why this is the case,” says Achim Weiss. The form of energy transport within the gas spheres and the mass loss from the surfaces are evidently decisive factors: “Models with greater mass, which have large convective cores, deliver clearer results.” Achim Weiss intends to continue the search for an answer to this question. By no means do we already know everything in astrophysics – even if we do now have a pretty good idea of “what the stars are.”

Provided by Max-Planck-Gesellschaft

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