From stardust to the solar system

The last article was devoted to the formation of the universe, the elementary particles and the formation of the first elements of the universe (Fig.1).

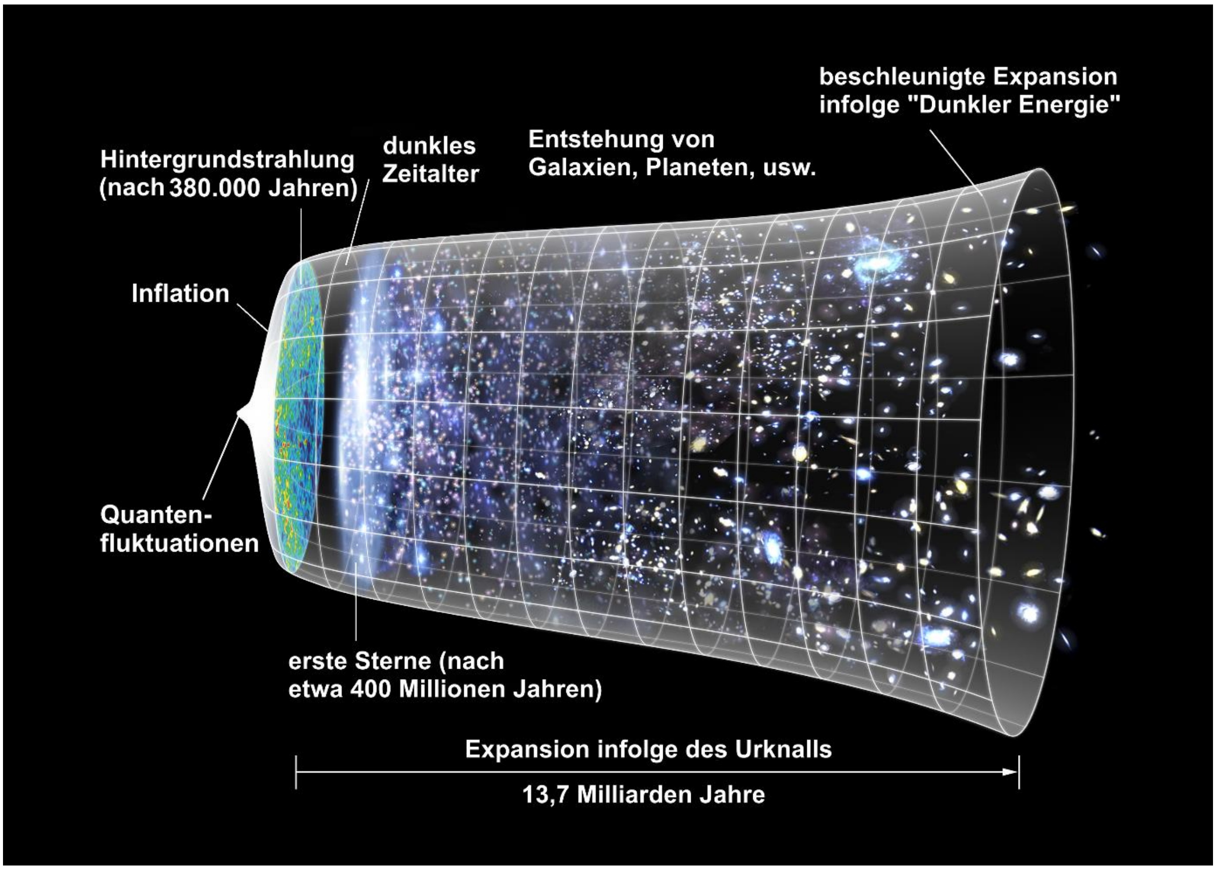

Abb. 1: Big Bang and expansion of the universe

About 75 percent of the mass of matter in the universe is hydrogen, and about 25 percent of the mass is helium. All of the heavier elements, including carbon, which we humans prefer to be made of, make up only about one percent of the total matter in the universe. When scientists look more closely at this one percent of matter that is not hydrogen or helium, other differences emerge. Some elements, such as carbon or iron, are relatively common, while others, such as beryllium or gold, are rare. Why is this so? Well, the answer has to do with the way the elements are formed. In the last post we learned that during primordial nucleosynthesis the first hydrogen and helium nuclei formed (with traces of lithium nuclei), these combined with electrons about 380,000 years ago to form the elements hydrogen, helium and lithium. These are the lightest elements in the universe (fig. 2).

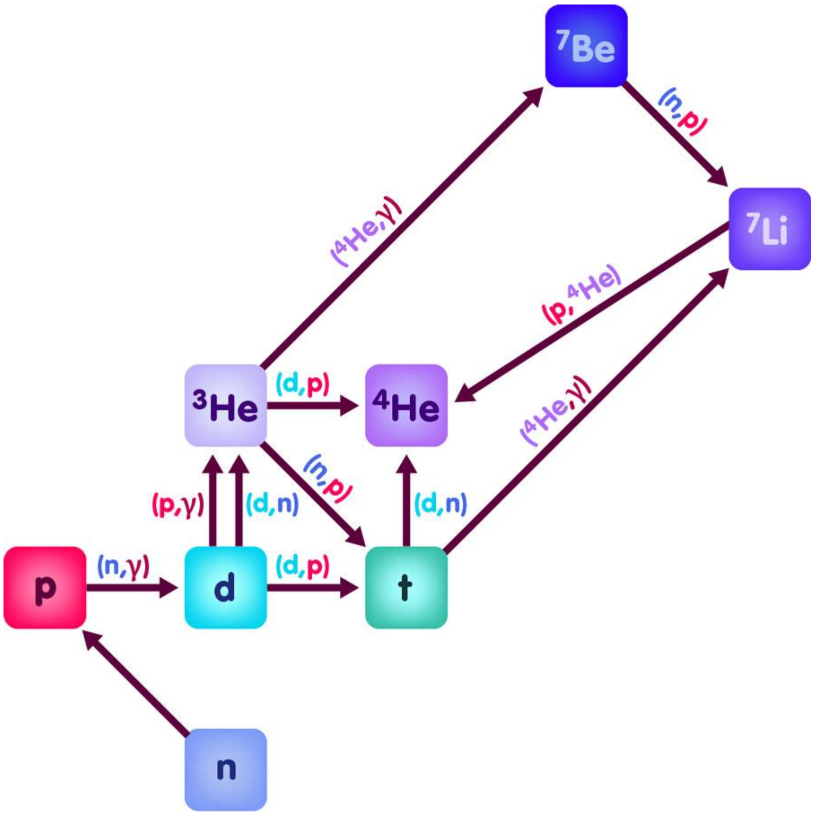

Abb. 2: Primordial Nucleosynthesis

Temperatures were too low during the expansion of the universe for the other elements of the periodic table to form. So what has to happen for this to come about? The answer is literally in the stars.

A star is born

A few hundred million years after the Big Bang, the hydrogen and helium that had formed in the early universe began to cluster together under the influence of gravity. Clouds of these elements continued to contract, becoming hotter and hotter - reversing the general cooling trend in certain areas of the universe. This point marks the beginning of the first epoch of star formation (Fig. 3).

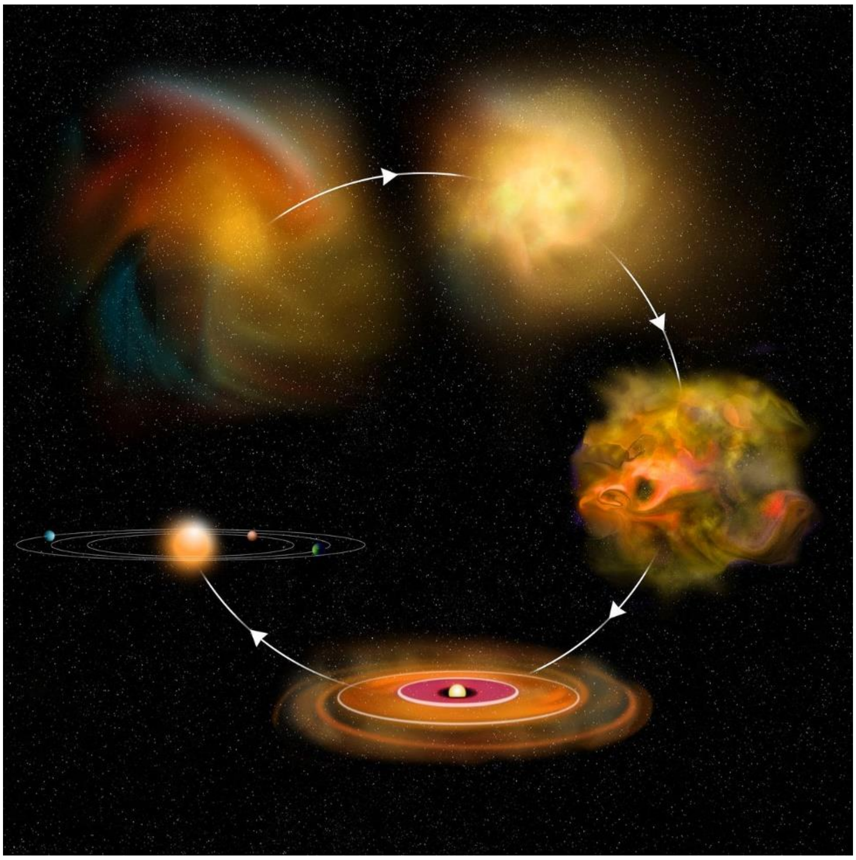

Abb. 3: Star Formation

As the cold hydrogen and helium clouds in space drew ever closer together, the matter inside these clumps became tremendously hot and dense - more than 10,000,000 Kelvin and 100 grams per cubic centimeter - that nuclear fusion reactions could again begin.

The result of this collision is the formation of a deuteron, in which a proton and a neutron combine, releasing two more elementary particles (a positron and a neutrino) and a certain amount of energy. This is the same nuclear fusion process that had occurred in the first moments of the universe.

The formation of chemical elements inside stars is called stellar nucleosynthesis (Fig. 4). In the dense formations that collapsed as remnants of the Big Bang, the fusion of two protons (two hydrogen nuclei) occurred first, and together they formed a deuteron. Under normal conditions, two positively charged particles repel each other, just like the positive poles of two magnets. But if the protons have enough energy and are moving fast enough (as they do in the hot regions inside most stars), they can overcome this repulsion and come close enough to stick to each other. The strong interaction is capable of doing this, but its range is limited. Pressure and temperature inside a star let the protons come into the sphere of influence of the strong force. The strong force grabs the particles and forces them together to form the atomic nucleus. Strictly speaking, it is the quarks within the individual protons that stick together through the nuclear glue - the gluons - and which now come so close to the quarks of the other protons that the gluons also hold them. The weak force does the rest and lets two protons decay to neutrons and ready is the helium nucleus.

This process, called hydrogen burning (Fig. 4), happens very slowly. Although protons collide many times a second inside a star, scientists have calculated that it takes an average of a billion years for one proton to fuse with another. Fortunately, stars have lots of protons!

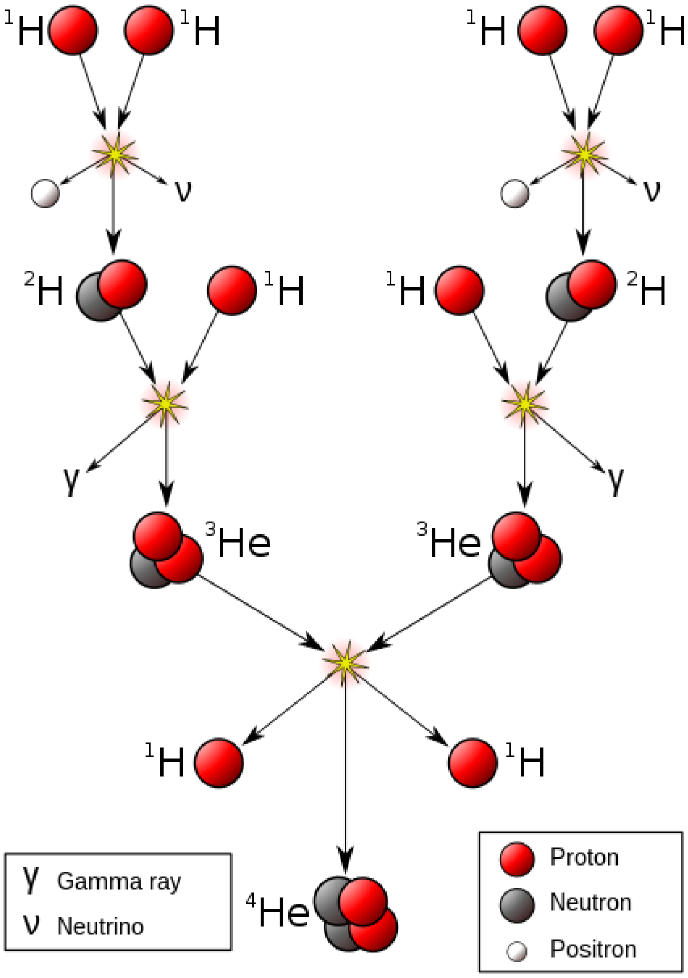

Abb. 4: Stellar Nucleosynthesis

After a deuteron forms, the next step in the formation of heavy elements happens relatively quickly. Within a second, another proton fuses with the deuteron to form a helium-3 nucleus.

Now different things can happen:

- Two helium-3 nuclei collide with each other and form a helium-4 nucleus, releasing two protons (Fig. 4).

- A helium-3 nucleus and a helium-4 nucleus (formed by the previous reaction) combine to form a heavier element, beryllium-7 (Fig. 5).

- Once a beryllium-7 nucleus has been formed, two more nuclear processes can occur:

- Beryllium-7 captures an electron and becomes lithium-7, which then collides with another proton to form two helium-4 nuclei (Fig. 5).

- Beryllium-7 collides with a proton to form beryllium-8, which can fuse with a positron, again forming two helium-4 nuclei (Fig. 6).

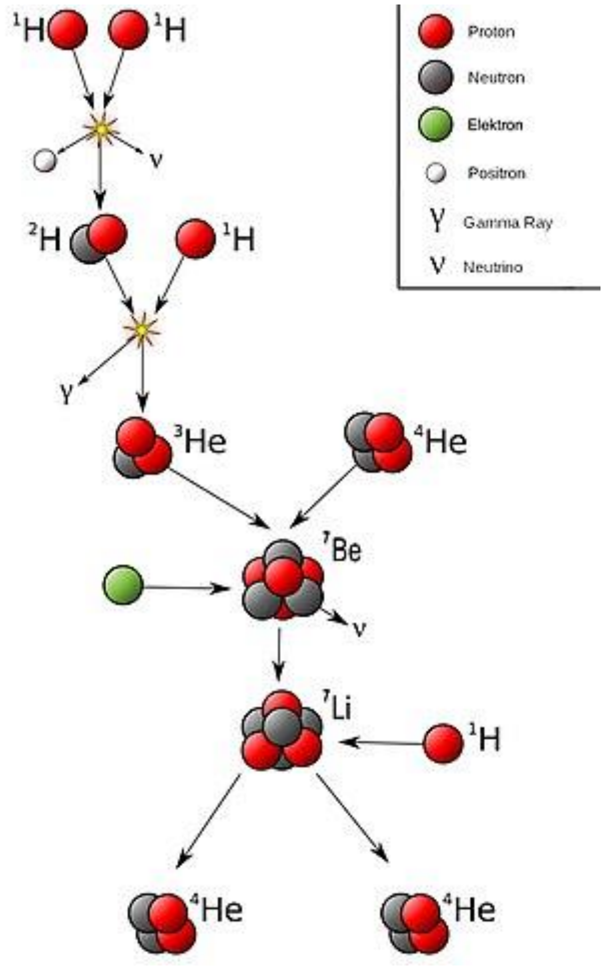

Abb. 5: Formation of Beryllium-7 und Lithium-7

Whether any or even all of these nuclear reactions occur depends on the physical conditions in the deep interior of a star. When the reactions happen, they occur at different rates, leading to the different ratios of the various elements we observe in the cosmos.

The end result is that four hydrogen nuclei are transformed into one helium nucleus, which consists of two protons and two neutrons.

But why does this process release energy and where does it come from? The protons and neutrons in the helium nucleus are held together by the gluons, so it would logically take energy to break the nucleus back down into its component parts. This energy is released as so-called binding energy during the fusion. Because energy is equal to mass ($E= mc^2$), the fused nucleus weighs 0.66% less than the sum of its initial parts. In this way, our sun fuses 564 million tons of hydrogen protons per second to about 560 million tons of helium. Our sun transforms the remaining 4.3 million tons per second into $3.85 * 10^{26}$ joules of radiant energy. This corresponds to more energy than mankind has released in its entire evolutionary history.

The binding energy of the fused helium nuclei is sent on its way in the form of hard gamma radiation. This collides directly with the particles in the surrounding plasma, exerting a pressure that stabilizes the plasma against its own weight. With each collision, the photons transfer energy to their favorite interaction partners, the free electrons. These pass the energy on to the rest of the plasma through collisions. The radiation is thus strongly hindered in its propagation by the plasma particles and therefore wanders around within the sun for millions of years. Thus the gamma radiation from the center of the star loses nearly all its energy on the way and drags itself with last strength as now visible light to the surface.

Three-alpha-Process and the Formation of Carbon

The very first stars used hydrogen, the simplest and most abundant element in the universe, as fuel to form helium and some other elements like lithium and beryllium, or more precisely, the isotopes lithium-7 and beryllium-8.

But there's a problem: beryllium-8 is actually incredibly unstable (the naturally occurring stable isotope of beryllium has five neutrons, not four). Beryllium-8 decays back into two helium-4 nuclei in a tiny fraction of a second - and therefore apparently does not live long enough to serve for the construction of heavier elements found throughout the cosmos.

This great mystery puzzled scientists for some time. How did the universe produce these heavier elements? In particular, how did the universe create carbon, which is made of six protons and six neutrons?

The English astronomer Fred Hoyle found the answer in the 1950s. Hoyle was fascinated by the carbon problem. He knew there had to be a way for a third helium nucleus, sometimes called an alpha particle, to attach to a beryllium-8 nucleus immediately after it formed - a process now known as the three-alpha process.

The first condition necessary for the three-alpha process to occur is the combination of high temperature and high density (Fig. 6).

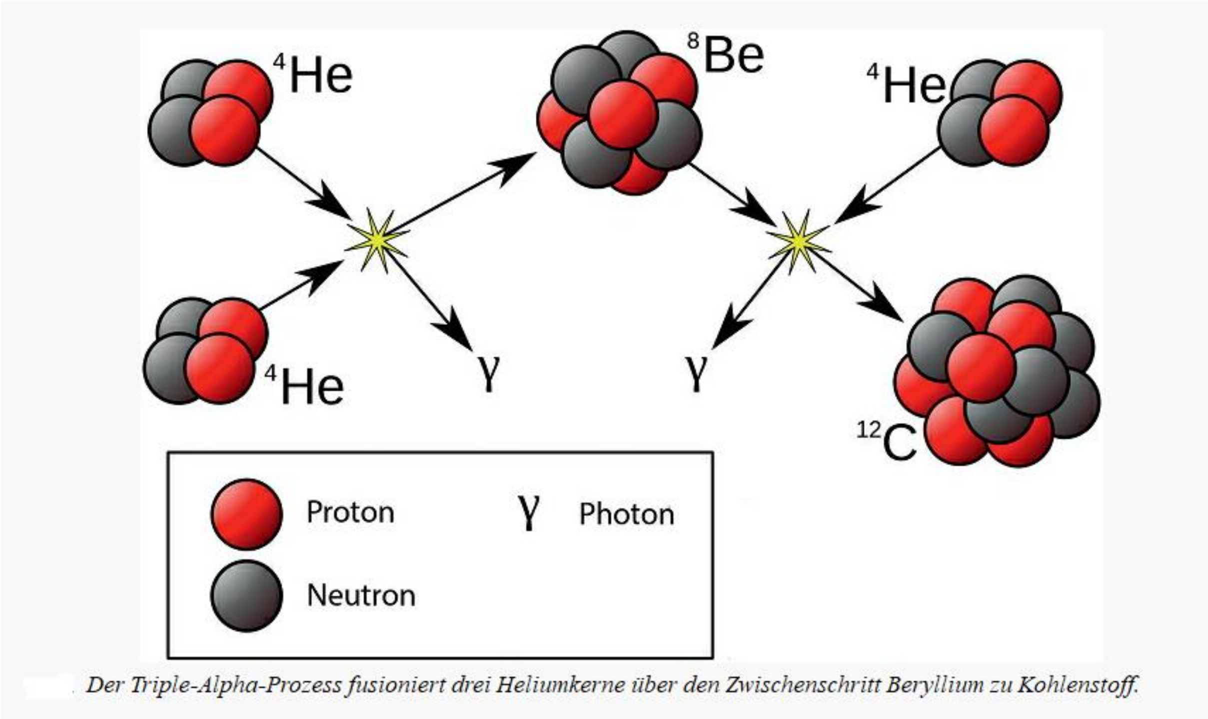

Abb. 6: Three-Alpha-Process

However, stars do not become hot enough to produce carbon until they have used up their supply of hydrogen, because when a star runs out of hydrogen, the pressure in its core drops, and the star shrinks under the inward force of gravity. This shrinking, in turn, produces a higher energetic state - the star becomes much hotter inside and builds up higher pressure. Hoyle reasoned that there must be a situation where the combination of beryllium-8 and helium-4 must have just as much energy as a carbon-12 nucleus in an excited state. Hoyle realized that because of quantum mechanics, atomic nuclei normally spend their time in a low-energy state. This state is called the ground state, but every now and then atomic nuclei absorb a certain amount of energy and are then in an excited state for some time.

When he did the calculations - adding the masses of beryllium-8 and helium-4, subtracting the mass of carbon-12, and converting the mass difference to energy using Einstein's $E = mc^2$ - he got a number. Hoyle predicted that carbon-12 must have an excited state, with an energy level or resonance of exactly 7.65 mega-electronvolts above the ground state.

When Hoyle first proposed this idea in the 1950s, there was no experimental evidence for such a situation. But Hoyle managed to persuade U.S. scientist William Fowler and his colleagues at Caltech's Kellogg Radiation Laboratory to test this hypothesis using a particle accelerator - and he was right in his assumption.

Formation of heavier elements

After a star has produced carbon, the buildup of the heavier elements continues step by step for a while (Fig. 7).

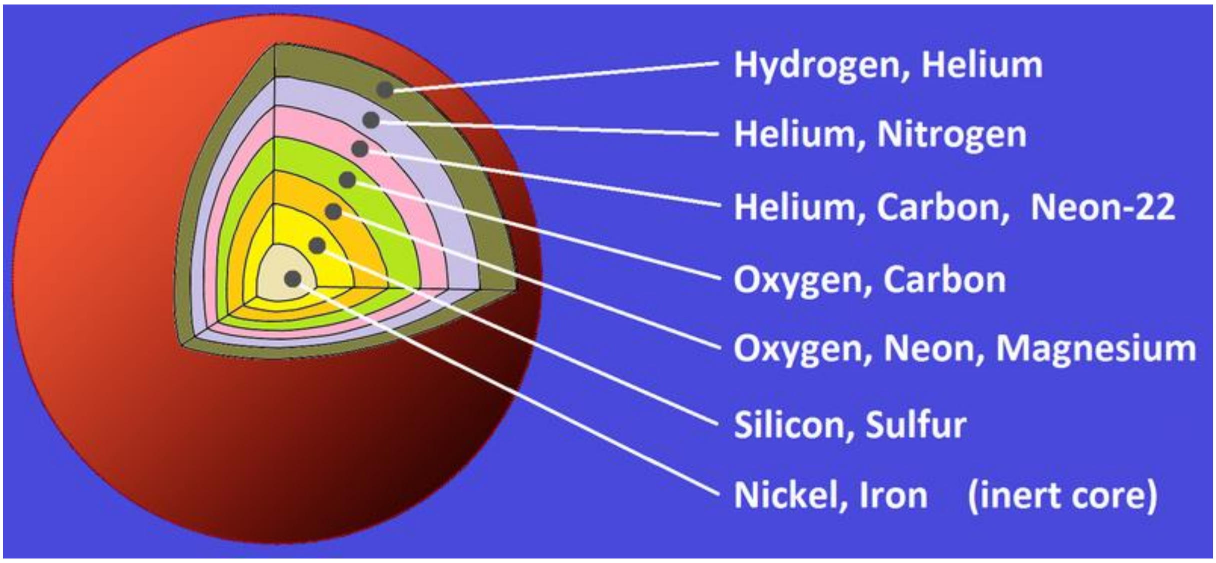

Abb. 7: Formation of heavier elements.

At the beginning, the star burns helium to carbon in its center until this supply is exhausted. Then the core contracts, and it gets hot enough for carbon-12 to form oxygen-16 with another alpha particle.

When the carbon is used up, the core contracts again, becomes hotter again, and more fusion processes can occur, forming heavier elements such as magnesium, oxygen, and neon.

In sufficiently massive stars, the process of stellar core burning repeats itself over and over, accompanied by further gravitational shrinking of the star's interior:

- The star burns an element until its abundance in the core is exhausted (although element burning may continue in shells further out from the star).

- The stellar material collapses toward the center of the star as gravity takes over for a period of time.

- The temperature rises.

- The products of the previous fusion processes are available as new fuel.

In sufficiently massive stars, the gradual conversion of helium into heavier elements continues until elements such as magnesium-24 and silicon-28 have been formed. In even hotter and even denser stars, the processes become more and more complex, some elements decay again and then form heavier and heavier atomic nuclei - on and on it goes in the periodic table until finally iron-56 is reached.

This nucleus is considered the most stable of all, consisting of 26 protons and 30 neutrons more tightly bound than is the case with any other element. So we have the most important elements of the periodic table, but by no means all of them. How did the other elements come to be formed? This is then actually related to the death of a star - a supernova.

Formation of heavy elements with supernovae

The death of a star is a process that in some cases is a fantastic fireworks display, releasing massive amounts of energy and scattering much of a star's matter in space. Most theories of stellar evolution hold that it is precisely this material flying through space from supernovae that causes the collapse of interstellar gas and dust, setting the stage for the formation of new stars (Fig. 8).

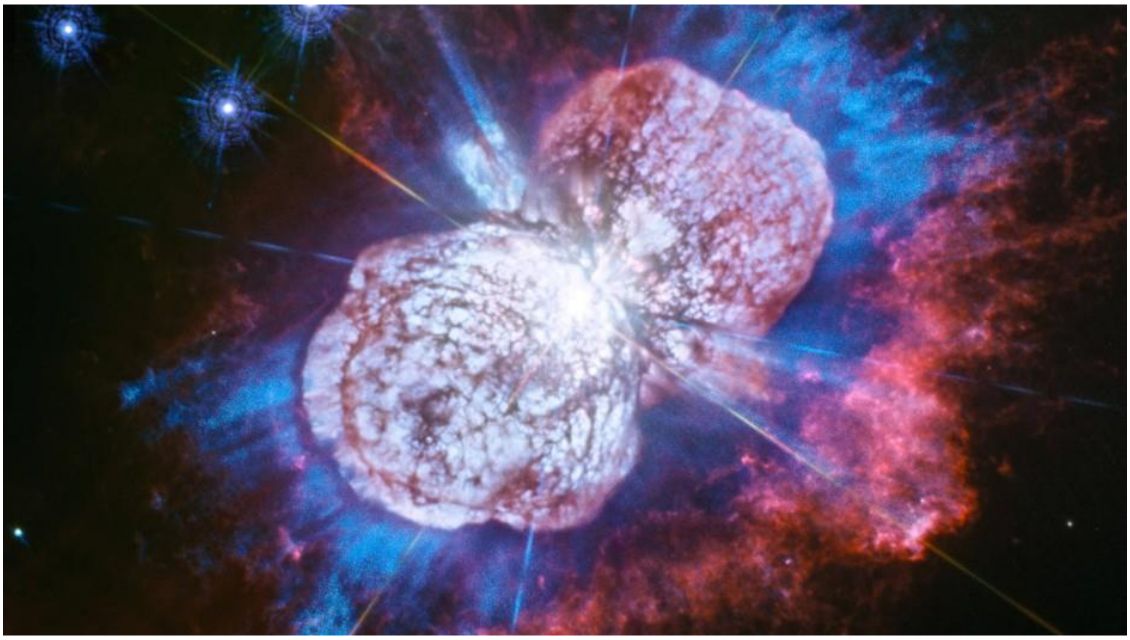

Abb. 8: Supernova

But this fate of an explosive end affects only a small fraction of stars, and those that are much more massive than our Sun. Most stars burn their hydrogen to helium, then helium to carbon, but then they do not get hot enough for carbon burning to produce oxygen. Instead, such a star shrinks and turns into a white dwarf, an inert lump of matter that has the mass of a star but the diameter of a planet. When a white dwarf forms, it is still very hot, and astronomers can observe its slowly diminishing light with their telescopes. A white dwarf can no longer draw energy from nuclear fusion, and scientists assume it will eventually cool to a cold black dwarf (Fig. 9).

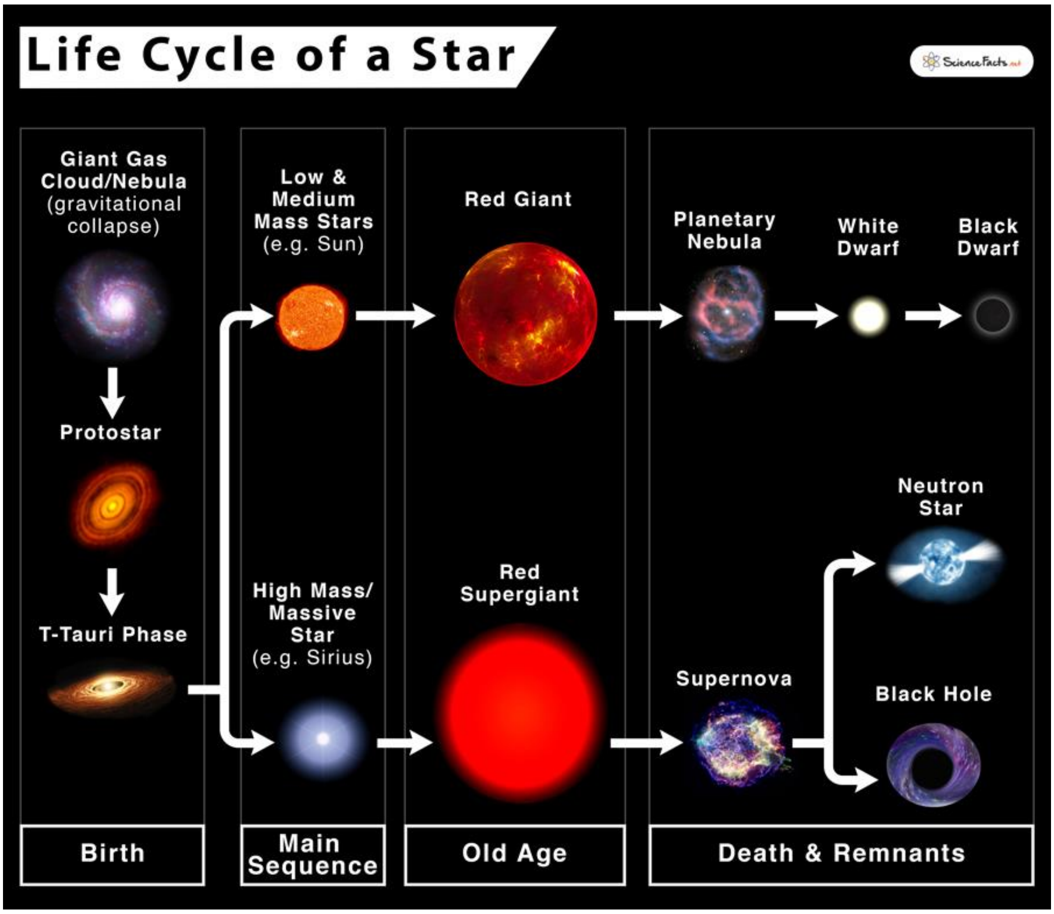

Abb. 9: Life Cycle of a Star

Stars several times the mass of the Sun face a more dramatic end - a supernova. Astronomers now divide supernovae into two main types (Fig. 10). These differ in how the stars involved have acquired the necessary mass.

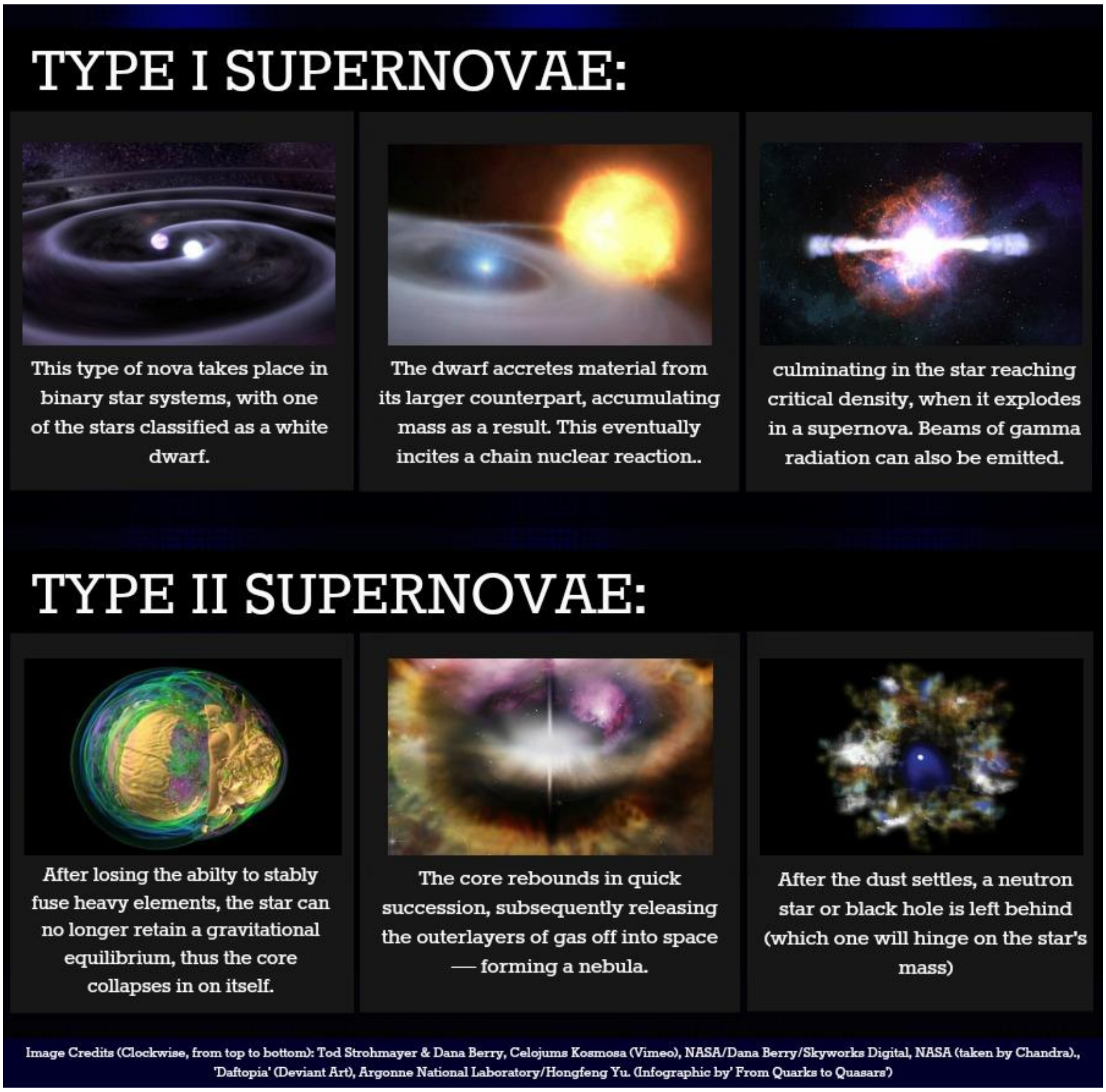

Abb. 10: Type 1 and 2 Supernova

Type I Supernovae

When a white dwarf has another star in sufficiently close proximity, the gravitational effect of the collapsed star (i.e., the white dwarf) may be large enough that it tears matter away from the companion and surrounds itself with it. If this amount of matter is large enough to bring the mass of the white dwarf above a level where the star is no longer able to resist the inward gravitational pull, then this results in a supernova explosion.

The critical mass for a supernova to flare is about 1.4 solar masses - a number known as the Chandrasekhar limit, named after astronomer and Nobel laureate Subrahmanyan Chandrasekhar, who first calculated it.

When a white dwarf crosses this boundary, a chain reaction of nuclear fusions begins, leading to one of the most spectacular spectacles in the universe - a supernova. Within seconds, the energy generated by the fusion reactions evokes an outward shock wave that hurls material outward at speeds of about 5,000 to 20,000 kilometers per second, producing an enormous flash of light - up to five billion times the brightness of the Sun.

Supernovae are so bright that early stargazers thought they were new stars that had formed in the sky - hence the name "nova" (for new). The name is paradoxical because supernovae are not new stars, but the dramatic last moments of an old star on its way to oblivion.

Type II Supernovae

Another class of supernovae involves stars more than nine times the mass of our Sun. After the various stages of nuclear fusion have been exhausted, the remaining mass is too high for a white dwarf to form.

In this situation, a core of nickel and iron builds up in the center of the star, eventually reaching the Chandrasekhar limit and then collapsing, with protons and electrons colliding to form neutrons and neutrinos.

The neutrons are so tightly packed that they exert a huge outward pressure. It is called degeneracy pressure.

As the outer layers of the star fall inward, they eventually hit the core and bounce back, sending shock waves that rip apart the overlying parts of the star in an explosion. This explosion is called a type II supernova.

In a galaxy the size of the Milky Way, Type II supernovae occur about once every 50 years. Depending on the initial size of the star, they can leave behind either black holes or neutron stars. Neutron stars are tiny - just 15 kilometers in diameter - but have about 1.4 solar masses and are tremendously dense. The gravity at the surface of a neutron star is so strong - about a trillion times stronger than on the surface of the Earth - that one would instantly assume the shape of a pancake.

The enormous energies released by a type II supernova create an environment in which elements heavier than iron can form.

Our Solar System

Our sun and solar system are about 4.6 billion years old (Fig. 11), and one may be tempted to believe that all stars have existed for such a long time. However, this is far from being the case. If we look around the universe, we can find stars that are just being born. In our galaxy, the Milky Way, scientists estimate that one star the size of the Sun is born every year - and about every year, one star dies.

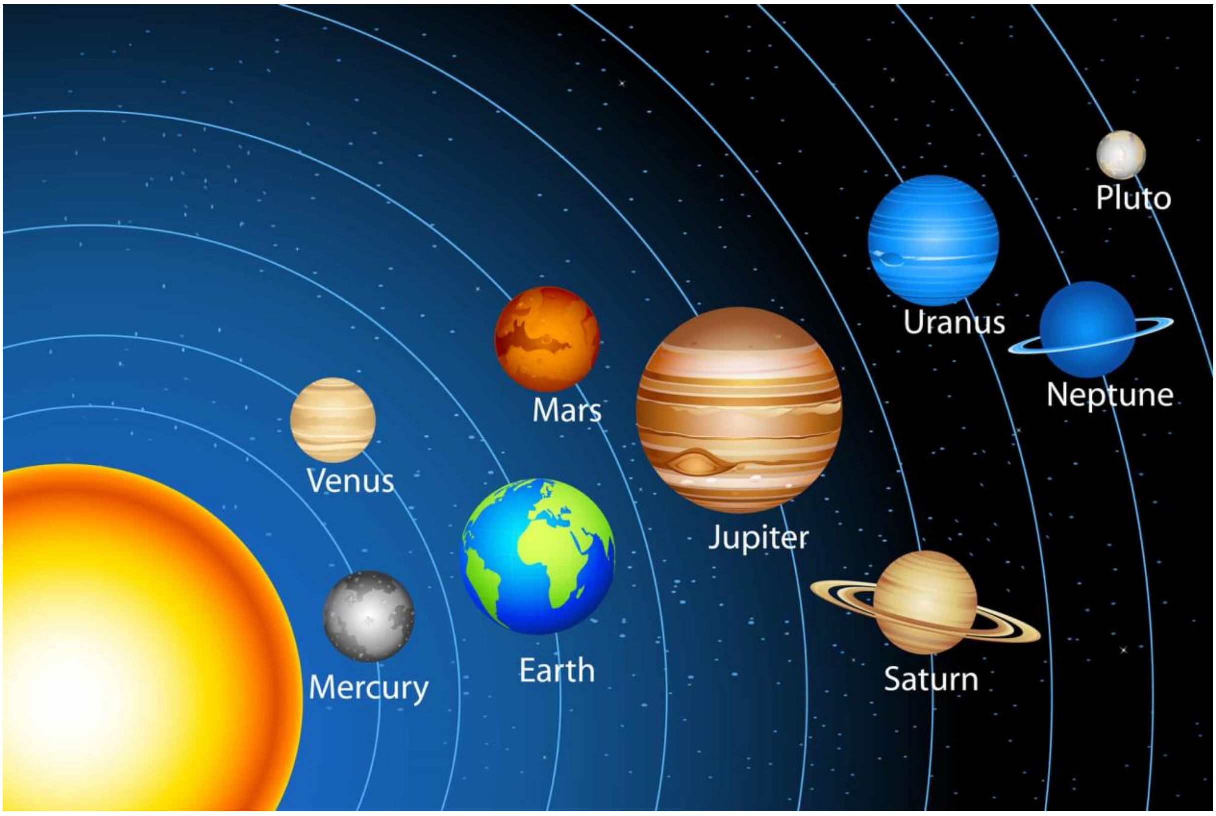

Abb. 11: Our Solar System

The observation that all planets move in a flat plane in the same direction around the Sun came about as soon as Isaac Newton's laws helped explain the motions of the planets. In addition, astronomers using the latest advances in telescopes had discovered large fuzzy clumps of gases in space, which they called "nebulae" (Latin for "clouds"). In the mid-17th century, the Swedish scientist Emanuel Swedenborg, the French mathematician René Descartes, and the German philosopher Immanuel Kant had independently proposed that our solar system had originated from a cloud of dust that rotated about a central axis. The exact physical basis of this system was described in the late 18th century by the mathematician and astronomer Pierre-Simon Laplace. This became known as the nebular hypothesis (Fig. 12).

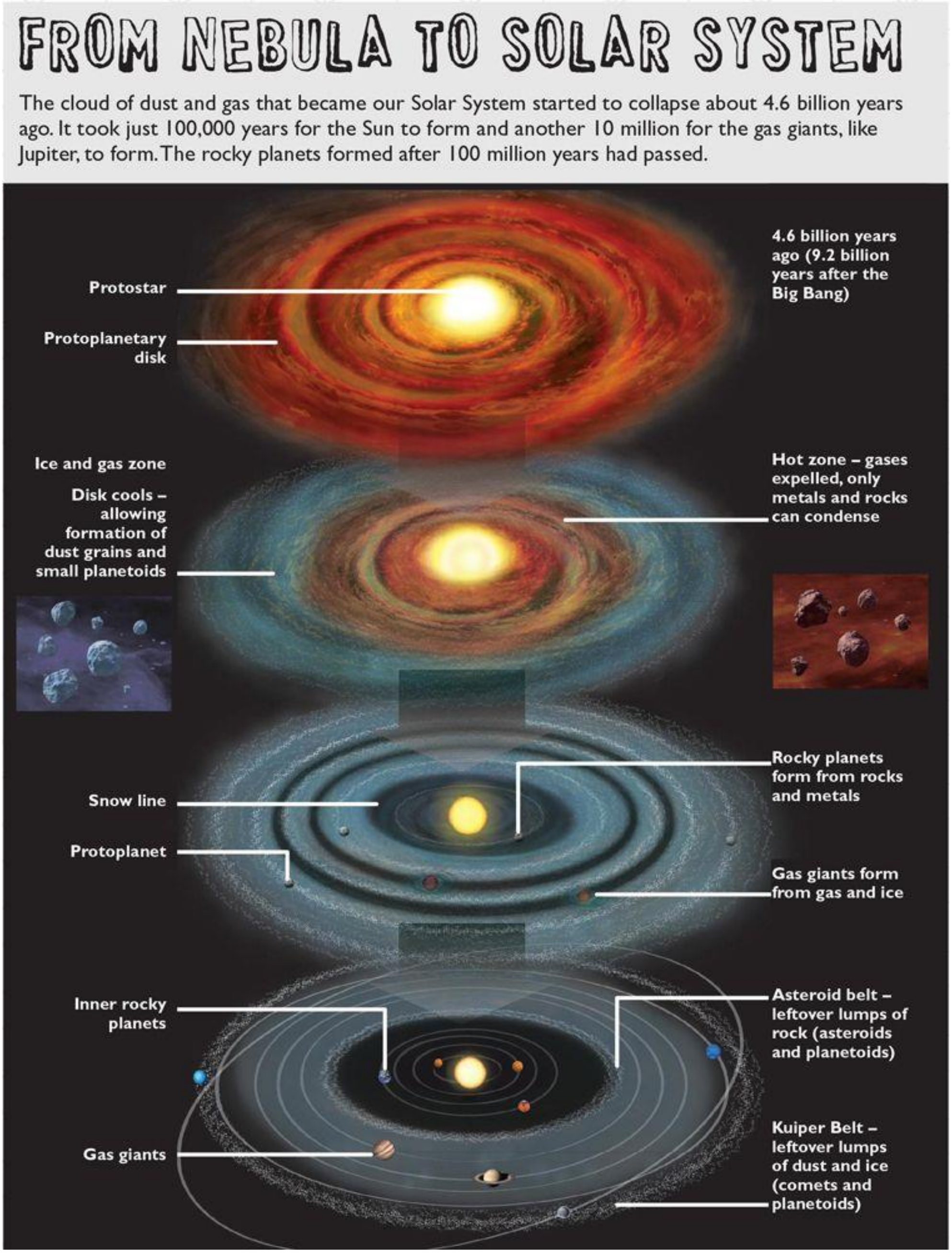

Abb. 12: Nebular Hypothesis

According to the Nebular Hypothesis, at the beginning the solar system consisted of a sphere of gases and matter, about 90% of which was hydrogen, 9% helium, and less than 1% all other elements. These nurseries of stars - large clouds composed of hydrogen and other gases - provide some of the most stunning images of the universe, such as the image of the so-called Pillars of Creation in the Eagle Nebula. Such nurseries of stars are found in the Milky Way. In 2004, for example, NASA's Spitzer Space Telescope found that a distant nebula called RWC49 contained more than 300 newly forming stars.

This nebula was slowly spinning on its axis. Eventually, this loose mass of cosmic dust began to compress, possibly due to the shock of a supernova from a nearby star.

After this initial shock, gravity takes over as the crucial shaping force of star formation. Gravity acts between the gas and dust particles.

Gravity is the weakest of all the fundamental forces in the universe. We owe our existence to this weakness. For if gravity were not so weak, stars would not be so immeasurably large. Because it is so weak, at least 10^{56} protons must come together in a star so that it can shine. Only then is the gravity of the whole ball of gas great enough to cause it to collapse under its own weight and build up such a high temperature and density inside it that atoms fuse together. If the gravity were a little stronger, much fewer atoms would be enough to make a gas ball become a star. The stars would then have less material. With the help of a stronger gravity, however, they would reach the same core temperature and thus the same fusion efficiency. The result would be a much shorter stellar life. In a universe with stronger gravity, therefore, there could be no planets and thus no life. The stars would not exist long enough for that.

The process of star formation starts very slowly, but eventually particles in the early solar nebula tend to move toward the denser regions in the center.

This process, called gravitational collapse, accelerates the rotation of the stellar nebula because of the law of conservation of angular momentum.

By the way, we are familiar with the law of conservation of angular momentum, even though we may not know its name. If we watch figure skaters spin, we will notice that they spin slowly when they have their arms and legs far from their bodies, but when they pull their arms and legs (and thus their mass) toward the center, they begin to spin faster.

So the spinning solar nebula not only speeds up as it condenses, but also begins to form a flattened disk. This is similar to spinning a lump of molten glass on its axis until it flattens out. The easiest way for the nebula's mass to resist angular momentum is to spread out into a flat disk.

The stellar nebula contains various globules, called globules, of gas and dust.

The collapse of the cloud also allows heat to be generated. The larger a globule is, the higher its temperature. Eventually, after tens of millions of years, each of the globules may have accumulated enough gas and dust that it can be called a protostar. A protostar is not yet a true star, but it is already quite hot inside. When the temperature inside the protostar reaches 10,000,000 Kelvin, nuclear reactions can begin, and the star begins to glow.

If a protostar does not collect enough gas and dust - perhaps because there is not enough material in the gas cloud surrounding it - it becomes an object called a brown dwarf. These objects are typically larger than the planet Jupiter, but smaller than the Sun.

Old stars, however, can also tell us a great deal about star formation.

For example, a star with the unspectacular designation HE1523-0901 is about 13.2 billion years old, making it the oldest known star to form about 500 million years after the Big Bang.

Although HE 1523-0901 is relatively distant, one can learn a great deal about the early history of the universe from it by studying its spectrum. The spectrum of HE1523-0901 is interesting because it contains not only hydrogen and helium, but also traces of the radioactive elements thorium and uranium. The presence of these metals means that the star was formed from the ashes of a supernova - the explosion of an even older star. We can be sure that this older star was one of the first to form in the universe.

As we already know, chemical elements heavier than lithium are formed inside stars. When massive stars reach the end of their lives, the heavy elements are dispersed in space by gigantic explosions called supernova bursts. Because such heavy elements can only be formed in this way, scientists have some clues about early stars at hand.

Heavy elements are distributed in varying abundance throughout the visible universe, but it appears that they are found in all stars. Therefore, the earliest stars that scattered heavy elements throughout the early universe must have lived very briefly and died very quickly as supernovae to lead to today's widespread and uniform distribution. To have concluded their lives so quickly, these first generation stars must have been very massive. (The more massive the star, the shorter is its lifetime, because the large pressure inside massive stars causes the nuclear reactions to proceed faster).

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