

The Birth of the Elements

By David Thielk



As you begin your study of chemistry, the task of learning about the millions of different chemical substances that make up your world seems hopelessly complicated. But you've probably already been surprised to find that all of them are made from only a few more than 100 different chemical elements combining in an infinite variety of ways. Even your own body—complex as it is—comprises only a few dozen of these known elements.

The fact that all matter is made from the combinations and recombinations of this short list of elements suggests a very basic question: Where did the elements that make up our bodies and all of our surroundings come from? Scientists believe they have the answer, and it shines with startling beauty: “We are made of stardust.”

The origins of hydrogen and helium

Astrochemists estimate that hydrogen makes up about 75% and helium about 25% of all of the matter in the universe today. Although many of the remaining elements seem abundant from our earthly point of view, they exist in only trace amounts in the universe as a whole.

Where did all of this hydrogen and helium originate? Scientists conclude that approximately 16 billion years ago, the matter of the entire universe was contained within a tiny but incredibly dense sphere. The explosion of this tiny sphere—the Big Bang—marked the moment when the universe began and both space and time came into existence.

Some remarkable things happened in those first few moments of time. The explosion occurred a mere 10^{-43} seconds after the Big Bang began. During the first second or so, highly energetic photons collided and converted their energy into mass, creating protons, neutrons, and electrons—components of future atoms. Within these first seconds, the temperature of the universe dropped from a high of about 10^{32} K down to about 10^{10} K. In another three minutes, the universe had cooled to 10^9 K or about a billion Kelvin—the temperature at which protons and neutrons can combine to form the nuclei of a few of the elements, like helium.

And then the action slowed down. In fact, as radiation and matter continued to spread out, temperatures dropped even further, and nucleosynthesis eventually stopped. At this stage, some nuclei existed, but no atoms. It was still too hot. It took another 300,000 years for temperatures to cool to about 3000 K—the temperature at which electrons, the

currency of chemical reactions, could combine with nuclei. Atoms were born and molecules soon followed.

Where do stars come from?

Stars are born in Giant Molecular Clouds (GMCs)—often located in the arms of spiral galaxies. Space isn't empty. It contains vast amounts of gaseous matter. The first GMCs were almost entirely hydrogen and helium. Today, they contain trace quantities of heavier elements as well. Inside a GMC, gravity acts to draw the gas molecules together. Just as a ball released from your hand loses potential energy and gains kinetic energy as it falls, the condensing gas molecules in the GMC convert gravitational potential energy into kinetic energy in the form of heat.

A star is born when the core temperature of a GMC reaches about 10 million Kelvin. At this point, a new kind of nucleosynthesis begins. The entire process involves several steps and can undergo a variety of stages depending on the presence of small amounts of heavier elements such as carbon and nitrogen. But by far, the most important events that accompany the birth of a star involve the net conversion of hydrogen nuclei into helium nuclei.

Why does this hydrogen to helium conversion release so much energy? Einstein's famous equation— $E = mc^2$ —holds the key. In simple terms, this equation says that mass and energy can be converted into each other. Accurate measurements of the masses of the reacting hydrogen nuclei and the resulting helium nuclei plus a few subatomic particles show that the product mass of this nuclear reaction is only slightly less than that of the initial hydrogen nuclei. But that's where the letter *c* becomes important. Since *c*, the velocity of light, is a very large number (3×10^8 m/s) and the square of *c* is even larger, a very small amount of mass releases an enormous amount of energy upon conversion.

Our own sun pours out energy at a rate of about 3.9×10^{26} Joules/second. To produce this much energy, about 700 million tons of hydrogen are converted to about 695,000,000 tons of helium every second. This means that our sun is converting mass to energy at the rate of about 5 million tons every second!

Once fusion begins in the core of the young star, the pressure (outward) from the fusion reaction balances the force of gravity (inward),



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and a star enters a relatively stable period that constitutes the main part of its life. Our own sun reached this point about 5 billion years ago. In another 5 billion years or so, the hydrogen at the core will run out. When hydrogen fusion stops, gravity will once again prevail. The core will collapse and generate more heat. As the temperature increases, a new round of nucleosynthesis will begin as helium atoms begin to fuse together.

There are several fusion pathways that can occur in a star, depending on its mass, but the basic process is this. When the hydrogen in the core of the star is used up, fusion of hydrogen nuclei into helium nuclei ceases. Without enough outward pressure to counteract the force of gravity, the star begins to collapse.

But all of this collapsing causes the helium core to heat up. Then the hydrogen that was once outside the core is drawn inward, compressed, and heated enough so that fusion of hydrogen into helium begins again. As the core collapses, its temperature eventually becomes hot enough (about 100 million K) to trigger the fusion of helium into heavier elements. At this stage of its life, a star consists of two shells—an outer one in which hydrogen is fusing into helium, and an inner one in which helium is fusing into heavier elements such as carbon and oxygen.

Eventually, there is no more helium fuel in the core. If the star is massive enough, another round of collapsing and core reigniting takes place producing three distinct layers—an

outer layer where hydrogen is fusing into helium, a middle layer where helium is fusing into heavier elements, and an inner core where heavier oxygen and carbon are fusing. This innermost fusing yields a variety of heavier elements, including neon and magnesium. The pattern of using up the core fuel, collapsing, and reigniting can occur several times, producing a variety of isotopes of the heavier elements—silicon, phosphorus, sulfur, calcium, and others.

But even stars cannot produce nuclei with atomic numbers greater than that of iron. Iron represents the element with the most *stable* nucleus—the nucleus of lowest energy. No additional energy can be released by fusing iron into heavier elements.

If stellar synthesis ceases with the formation of iron, where do the heaviest elements come from?

The heavy elements

Although scientists understand the formation of lighter elements better than the formation of heavier elements, they are confident about the sources. Although some of the heavy elements originate within steadily burning stars, most of our heavy elements form as a result of a spectacular astronomical event called a *supernova*.

The majority of stars fade away as white dwarfs. But after a very massive star spends its fuel in the series of nuclear fusion cycles already described, its core begins to turn to

iron. Iron, the element with the most stable nucleus, cannot undergo fusion. When the iron core becomes massive enough, there is no longer enough fusion occurring to produce the outward force necessary to counteract gravity. At this point, the core of the star collapses under its own weight.

This collapse crushes the nuclei and free electrons, transforming the core into one made entirely of neutrons. Even though it took the iron core of this star millions of years to form, in a single instant, it transforms entirely to neutrons. With a diameter of only 20 km or so, the neutron core is small—but unbelievably dense! A mere teaspoon of this core material would weigh about 50 billion earthy tons.

And then the explosion! The supernova detonation occurs when the material of the outer layers of the star falls rapidly toward the neutron core. The core—no longer collapsing—is now a hard surface, off of which the outer material bounces. The result is a shock wave that propagates outward, blasting the outer core of matter so violently that nuclear particles are forced together, creating elements heavier than iron. These heavy elements blast into space where they may eventually condense with other materials to generate even more stars. Indeed, scientists think that the encounter of a shock wave produced by a supernova and a GMC is responsible for vast numbers of new stars.

Cosmic recycling

With the life and death of each star, elements are created, transformed, and recycled. The hydrogen in the air we breathe has probably been around since the Big Bang. The iron in our blood may have had its origins in the core of a star. Even the gold in our jewelry may have a history that includes a supernova shock wave.

Maybe you feel insignificant when looking up on a starry night. You may think how infinitesimally small one human seems when compared to the vastness of the universe. But there is something grand in what you share with all humans, living things, continents, oceans, planets, moons, and suns. We are all of the same stuff—the stardust of a younger universe. ▲

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