

ORIGINS OF THE ELEMENTS (NUCLEOSYNTHESIS)

All liquids, gases, and solids found on our planet are made from one or more of 92 naturally occurring elements. From what they have observed, scientists have determined that these same 92 elements are found throughout our universe. This suggests that a common process leads to their creation. But how are these elements created? How did they get so widely disseminated?

Currently, the most popular theory states that the nuclei of hydrogen and helium, the lightest and most abundant elements in the visible universe were created in the moments following the Big Bang. All other naturally occurring elements were – and continue to be – generated in the high temperature and pressure conditions present in stars. Elements are composed of tiny particles called atoms that are indivisible under normal conditions. However, when exposed to high heat and pressure, atoms can either break apart or fuse together. Under these conditions, the nucleus of one element can fuse with the nucleus of a different element, creating the nucleus of a heavier element. When elements lighter than iron form, the mass of the new nucleus is less than the combined mass of the two original nuclei. The difference in mass between the two is released as energy. In stars, this kind of reaction is referred to as stellar nucleosynthesis, but it is more commonly known as nuclear fusion. Nuclear fusion is used today on Earth in the nuclear explosives called hydrogen bombs. Many people hope that one day nuclear fusion will be used for peaceful energy production.

Stars are fueled by nuclear fusion reactions, which take place in their deep interiors, or cores. Hydrogen nuclei fuse, forming helium nuclei. The energy produced by these fusion reactions prevents the star from collapsing under its own gravity. Mature stars contain enough hydrogen nuclei to last billions of years. When a star's hydrogen fuel supply is spent, however, its core begins to contract. The contraction is so intense that it creates conditions under which helium nuclei fuse. In this way, helium becomes the star's next fuel source. The fusion of helium nuclei produces carbon and oxygen nuclei, and in the process sufficient energy is released to temporarily sustain the star.

Once helium runs out, the nuclei of carbon, oxygen, and other elements begin to fuse. These new fuel sources are depleted at faster and faster rates. Since the heaviest element created in a star by nuclear fusion reactions is iron, a large iron core eventually forms at the center of everything. At this point, gravity becomes overwhelming, the core collapses, and an explosion occurs, during which outer layers

of gas and heavy elements are ejected to space. Such explosions, called supernovas, occur about once a century in our galaxy. The energy created by supernovas produces nuclei heavier than iron. This process is known as supernova nucleosynthesis.

Long ago, scientists learned that they could heat atoms of an element to a glow and direct the light through a prism to produce a set of colored lines. These spectral lines are unique for each element: No two elements produce the same colors and line positions along a spectrum. By using instrumentation that reads light signatures from far away – a technique known as spectroscopy – scientists today know with great certainty which elements a planet or a star, or even a star's dispersed remnants, contains. All matter is made up of atoms -- elements comprised of smaller particles such as protons, neutrons, and electrons. The number of protons within the nucleus -- the central component of the atom -- determines the type of element. An element can have different forms, called isotopes, based on the number of neutrons in the nucleus. For example, an ordinary hydrogen nucleus contains just one proton. But deuterium, an isotope of hydrogen, has one proton and one neutron in its nucleus.

The entire universe shares a common set of elements. In the very early universe, the only elements were hydrogen and helium. But since the formation of stars, lighter elements within the stars began fusing to create heavier elements, producing all the other naturally occurring elements. Under the extremely high temperatures and pressures within the core of stars, atoms collide at high enough speeds to overcome the usual electromagnetic repulsion of nuclei, allowing nuclear fusion to occur.

All stars live by fusing hydrogen into helium. In the first step of the process, two hydrogen atoms fuse to form deuterium. In the next step, another hydrogen atom fuses with the deuterium, creating a rare isotope of helium that has two protons and one neutron in its nucleus. In the third step, two of the rare helium atoms fuse to create a single normal helium atom and two hydrogen atoms. The fusion pathway described above requires six hydrogen atoms to create one helium atom -- however, there are two hydrogen atoms left over at the end of the process. The net result is that it takes four hydrogen atoms to make one helium atom. The energy that fuels a star is a result of the difference in mass between the original four hydrogen atoms and the resulting helium atom. Following Einstein's mass-energy relationship, $E=mc^2$, the missing mass is converted to energy.

At even higher temperatures and pressures, heavier elements are able to form. Many are made from a process called "helium capture," in which a heavier element fuses with a helium atom. For example, helium fuses with carbon to make oxygen, and helium fuses with oxygen to make neon. Heavier nuclei can also fuse with each other, such as when carbon and oxygen fuse to make silicon or two silicon atoms fuse to make iron. Eventually, the interior of a massive star begins to resemble an onion, with different elements being created in different layers. However, elements heavier than iron are only produced in the extraordinary conditions created by the collapse and explosion of a star -- a supernova.

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