

THE INCREDIBLE ORIGIN OF THE CHEMICAL ELEMENTS – INCLUDING THOSE IN YOUR OWN BODY!

Hydrogen and helium - made in the Big Bang

According to most cosmologists the Universe began in a "Big Bang" - a kind of cosmic explosion in which all the matter and energy that would ever exist were created - about 15 billion (15 000 million) years ago. Time also began at this moment. At first, it is believed, the Universe was immensely hot and compact, though cooling and expanding rapidly. Matter was certainly not in the form that we know it on Earth. No elements or compounds existed. The temperatures were so high as to shake any such groups of particles to bits instantly. Even protons and neutrons were unable to form from their constituent particles, quarks.

Immediately after the Big Bang (about 10^{-32} seconds), the Universe probably consisted of a mixture of quarks and electrons (the ultimate building-blocks of matter), together with electromagnetic radiation. After about 1 second it had cooled enough for the quarks to come together to form protons and neutrons. A little later the temperature was no longer high enough (about a billion °C) to overcome the strong nuclear force which attracts protons and neutrons to one another, so pairs of these particles were able to come together to form the nuclei of deuterium (the heavy isotope of hydrogen). These nuclei then combined with further neutrons and protons to form the nuclei of helium-4 (2 protons and 2 neutrons), as well as small amounts of lithium and beryllium. A great many protons remained free, however, ready to form the nuclei of hydrogen atoms. (Neutrons decay into protons and electrons if left on their own.)

After a few hours the production of new elements had essentially stopped. The Universe continued to expand and cool for a million or so years until the temperature had dropped to a few thousand °C. This temperature was too low to keep the nuclei and electrons apart. Nuclei attract electrons via the electromagnetic force, which is much weaker than the strong nuclear force.

Protons and helium nuclei accepted electrons to form hydrogen and helium atoms respectively. These elements have survived to this day with little change in their ratio: about 88.6% of atoms are hydrogen and another 11.3% are helium, thus accounting for 99.9% of all atoms in the Universe. (By mass the figure for hydrogen is about 66% since hydrogen atoms are much lighter than helium atoms.) This might have been the end of things, except for the force of gravity, the universal force by which all matter attracts all other matter. Although extremely weak when compared with the other forces, such as electromagnetism, gravity has had a huge role in shaping the Universe we know.

Stars - the element factories

In the expanding Universe, small irregularities were present. Regions of higher density than average had stronger gravitational fields, attracting matter towards themselves more strongly than surrounding regions of lower density. That meant that the denser regions gradually became even denser, and so drew more and more matter towards themselves.

Particles of matter falling towards a common centre of gravity accelerate and so gain kinetic energy: the

matter becomes hotter. In the centre of such a mass of matter, the temperature eventually becomes high enough (about 10 million °C) to allow nuclear fusion to take place. Hydrogen nuclei collide with one another with such force that they overcome the mutual repulsion caused by their positive charge, and fuse together to form helium nuclei. This process releases a great deal of energy in the form of heat and radiation. The matter begins to glow we call the result a star. The radiation flowing outwards from the centre of the new star pushes against the incoming matter and prevents it from collapsing any further, holding it back against the force of gravity. Thus the star reaches a state of equilibrium, shining steadily.

In fact, stars are not created one by one. Rather they are made by the hundred million, in huge clumps called galaxies; such is the scale of the Universe. The Milky Way that you can see on a clear night is just a small portion of our own local galaxy, seen from such a distance that the millions of stars look like a faint milky stain on the dark heavens. There are billions of other galaxies in the Universe.

Stars come in a wide range of sizes. The heaviest and brightest stars use up their hydrogen very fast: perhaps in as little as 100 million years, though smaller stars take much longer, and some of the "first generation" stars (formed shortly after the Big Bang) are still shining. After about 90% of the hydrogen is used up the outward flow of radiation dies down and can no longer prevent the outer parts of the star from falling in towards the centre. The star shrinks in on itself, but in doing so it heats up further, to the point where helium nuclei can overcome their mutual repulsion arising from their charges, and start to fuse together. This becomes possible at about two hundred million °C.

Depending on the mass of the star, any remaining hydrogen (about 10% of the original amount) may be blown off to form a huge glowing envelope around the core: the star becomes a "red giant". This will be the fate of our Sun one day, though being a rather small star it has a relatively long life and will survive virtually unchanged for several billions of years yet. When it does become a red giant, however, it will mean the end of all life on Earth, since the envelope of hydrogen, at several thousand °C, will engulf the Earth as well as the other inner planets of the Solar System.

In a star undergoing helium fusion, unstable beryllium-8 nuclei are first formed from the fusion of two helium-4 nuclei, and then act as a sort of "reactive intermediate", since they readily fuse with a further helium-4 nucleus, resulting in the production of carbon-12. Carbon-12 nuclei themselves fuse with further helium-4 nuclei to form oxygen-16, and by repeating the same process, neon-20 and then magnesium-24. It is no accident that amongst the lighter elements the most common isotopes have mass numbers which are multiples of 4.

Other processes build up small quantities of heavier elements. These processes involve the decay of unstable nuclei. In this process, neutrons are emitted and then captured by other nuclei, so producing atoms with greater mass numbers. These neutron-rich nuclei are unstable and decay in turn. The excess neutrons decay into protons and electrons. The electrons are thrown out, and are known as β -particles. The result is a nucleus with a more even mix of protons and neutrons giving a stable atom.

As the nuclear fuel of the star becomes depleted, further contraction and heating occur, resulting in new nuclear processes which release energetic α -particles (helium-4 nuclei), capable of converting lighter nuclei into heavier ones. In this way silicon-28, sulfur-32, argon-36 and calcium-40 are formed. Some isotopes are unstable and disintegrate to give other isotopes. Such processes broaden the range of nuclei formed.

Eventually all the nuclear fuel of a star is exhausted and the outflow of radiation dies down. What happens then depends on the mass of the star. Stars like our Sun, or lighter, shrink to become "white dwarves" and then gradually die, but may occasionally undergo explosive changes throwing out large amounts of matter into space, including all the elements they have built up. Stars several times as

massive as our Sun, or heavier, shrink catastrophically, forming "neutron stars"¹ or even "black holes"². In many cases an enormous explosion (known as a "supernova") results, throwing much of the outer part of the star into space. During its dying moments, just before it explodes, the temperature of the star rises as high as three billion °C or more. At these temperatures many nuclear processes occur which result in the production of large amounts of elements in the middle mass range, such as the metals of the first transition series (iron to copper). Iron, being the most stable element, from the nuclear point of view, is produced in the greatest abundance. As the outer layers of the star are blown away, the inner regions throw out huge numbers of neutrons. These catch up and bombard the outer regions as they speed away from the centre. In this way further amounts of heavy and not-so-heavy elements are formed.

In the course of time the gas and dust ejected by a supernova mixes with the hydrogen and helium left over from the big bang. Today the density of this gas is very low, with only an atom or so in each cubic centimetre. Nevertheless there is still enough matter present that new stars are being formed even now. Our Sun was born fairly recently in the history of the Universe, about five billion years ago. It is a second (or perhaps third) generation star since it was formed from the remnants of earlier stars. For this reason it contains about 2% of heavier elements, mixed in with hydrogen and helium.

The Composition of the Earth

As the Sun was formed from a collapsing mass of gas and dust about four and a half billion years ago, other smaller bodies were also formed in orbit around it. One of these was the Earth. At first it was cold and relatively large, but as it shrank under its own gravity it heated up considerably, though nowhere near enough to start nuclear fusion as in the Sun. Being much lighter than a star, its gravity was too weak for it to hold on to much of the lightest elements, particularly hydrogen and helium. This is why these elements are much less common on (and in) the Earth than in the Universe as a whole. There was probably no atmosphere at all around the Earth at first, but as the heat built up it melted, allowing the heavier elements to sink to the centre, whilst the lighter ones floated on the top. Gases such as carbon dioxide and nitrogen were expelled from the molten rocks, as a result of chemical and physical changes, to form an early atmosphere devoid of oxygen but rich in carbon dioxide, ammonia, hydrogen sulfide and other gases. Later bombardment by icy comets may have introduced much of the hydrogen and oxygen we see today as water.

The atmosphere today is about one fifth oxygen. This is a highly unstable situation, since oxygen is so reactive, and was only brought about and maintained by the emergence of photosynthesising organisms on the earth – before that, oxygen was a deadly poison! Indeed, it is speculated that the production of oxygen by life almost led to the extinction of all life on Earth!

The core of the Earth today consists predominantly of iron, but with small amounts of other lighter and heavier elements, including radioactive isotopes of potassium, thorium and uranium. The breakdown of these latter, which is strongly exothermic, has kept the interior of the Earth hot to the present day, and this heat is responsible for volcanoes and continental drift ("plate tectonics"). The outer layers (the lithosphere, including the crust) are composed of lighter elements. The most abundant of these is oxygen (about 46.60% by mass of the total), followed by silicon (about 27.72%), aluminium (8.13%), iron (5.0%), calcium (3.63%), sodium (2.83%), potassium (2.59%), magnesium (2.09%) and titanium

¹ A typical neutron star has two or three times the mass of the Sun and yet is only 10 or 20 kilometres in diameter. Thus it has a huge density of about 10^{17} kg m⁻³. As a result, a teaspoonful would weigh about five hundred million tons!

² A black hole is a material body which has such a high density, and consequently such strong gravity, that not even light can escape from its surface (more strictly, the *event horizon*). Although the black hole itself can emit (virtually) no radiation, matter falling into it gets extremely hot and emits high energy radiation, revealing the position of the black hole.

(0.57%), hydrogen (0.14%), and phosphorus (0.11%). In addition, 11 other elements are present in trace amounts of from 0.02 to 0.1%. These elements are carbon, manganese, sulfur, barium, chlorine, chromium, fluorine, zirconium, nickel, strontium, and vanadium. The elements are present in the lithosphere almost completely in the form of compounds rather than in their free state. These compounds exist almost entirely in crystalline forms, so they are, by definition, minerals.

There is very little hydrogen in and on the Earth compared with its abundance in the Universe as a whole. There is essentially no free hydrogen present in the atmosphere, although small amounts are present as water vapour. In addition hydrogen makes up about 11% by mass of sea water, but water only accounts for 0.022% of the mass of the Earth as a whole.

Sources:

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3. Hawking S.(1995). A Brief History of Time. London: Bantam Books. pp 130-133