

The origin of elements

For life we need some complexity, and random individual particles don't seem a likely option (although some science fiction authors might disagree). We really want many particles to come together in relatively long-lasting structures. That is, we need molecules. This already tells us that we need to wait for quite a while. For example, even 380,000 years after the Big Bang, the universe had a temperature of nearly 3,000 K, which is too hot for complex molecules to exist. Later is better.

Our next criterion is that atoms, the building blocks of molecules, have to be able to come together in long chains. We can approach this by assuming that initially we have only the simplest element to determine if that works, then the next simplest, and so on.

The simplest element is hydrogen. Can hydrogen, by itself, form complicated molecules? No! At low enough temperatures (below around 500 K) it can form H_2 , but that's all. The reason is that the tightest electron shell has space for two electrons, but not more. Hydrogen has one electron, so it's happy to share with something else (such as another hydrogen), but once that inner shell is filled, hydrogen doesn't like to react any more. Hydrogen does play a critical role in life on Earth, both as a component of water and as a major player in organic molecules, but it needs help.

The next simplest element is helium. Can we combine many hydrogen and helium atoms together in complex molecules? No! We already discounted hydrogen by itself, and helium is even worse. Helium already has both electrons in the inner shell, which makes it by far the most nonreactive of all elements. We need to go higher.

The next three elements are lithium, beryllium, and boron. The problem with these is that there are vanishing amounts of them in the universe. To be completely open-minded we should think of these as possibilities, but we need to go farther as well.

The following three elements are carbon, nitrogen, and oxygen, and here we finally have very realistic possibilities. Carbon in particular has by far the most flexible chemistry of any element, and nitrogen and oxygen are also essential components of all known living things. We therefore need an epoch in the universe when elements heavier than helium exist in abundance, and probably up through oxygen. If such heavy elements have been present all the time, we're set. However, as we now describe, only hydrogen and helium were produced in the early universe.

Big Bang nucleosynthesis

"Nucleosynthesis" means the production of nuclei. In the very early universe one had protons and neutrons swimming around independently, and it would be hundreds of thousands of years until electrons could join nuclei in atoms. However, in the first few minutes

of the universe, protons and neutrons were able to come together to form some light nuclei.

So that you don't get too lost in the details, here is the basic summary of the process:

- When the universe is very hot, $T \gg 10^{10}$ K, neutrons and protons have about the same abundance.
- However, any nuclei that form at this stage (e.g., deuterium, via $p + n \rightarrow d + \gamma$) are immediately split by high-energy photons (via $d + \gamma \rightarrow p + n$).
- When the universe is much older than the lifetime of a neutron in free space ($\sim 10^3$ s, at which point the temperature is around 4×10^8 K), any remaining free neutrons will have decayed: $n \rightarrow p + e^- + \bar{\nu}_e$. No nucleosynthesis can proceed beyond this point until stars form vastly later.
- However, there is a sweet spot between these phases, when there are free neutrons around that can combine with protons without immediately getting separated again. In this phase, the light elements form.
- In principle one could imagine (as George Gamow did) that one would be able to produce *all* elements this way. However, there are no stable nuclei with 5 nucleons or 8 nucleons, so this means there is a bottleneck that prevents additional nucleosynthesis (basically because hydrogen and helium-4 are by far the most stable and common things around, but H+He and He+He both make unstable things).
- The relative abundances of H, D, He, etc. depend on the relative numbers of baryons and photons in the universe. Therefore, given a measured baryon fraction the relative abundances are all predicted with no free parameters. This is a strong test of the standard model.

Now let's discuss these in some more detail. The universe at a really tiny age (nanoseconds, say) was such a hot place that even protons and neutrons didn't exist. Instead, there was a soup of quarks and gluons (the things that bind quarks together). Eventually things cooled down enough that the quarks came together as protons and neutrons (and electrons and positrons were abundant as well). However, complex nuclei require combinations of protons and neutrons. For example, the most common isotope of helium (^4He) has two protons and two neutrons. Early on complex nuclei were being produced all the time, but until the temperature dropped enough it never stayed that way: a complex nucleus would get hit by a high-energy photon and split apart almost as soon as it formed.

After some tens of seconds passed (yes, it's that short a time!), the universe cooled down enough that if nuclei formed, they stayed formed. At this point, most protons were in ordinary hydrogen (which is just a single proton with no neutrons), and most neutrons were bound up in ^4He . Neutrons that were left over floated around in the ever-decreasing

density of space, eventually decaying into a proton, electron, and antineutrino. After several minutes had passed, no further nuclei had formed.

Why is this, though? Fusion takes place when combining nuclei can make them more energetically bound than they had been. The problem here is that (1) ${}^4\text{He}$ is by far the most bound of the light elements, so that (2) essentially only hydrogen and ${}^4\text{He}$ were around after a couple of minutes. Yes, there were trace amounts of lithium, beryllium, and an isotope of hydrogen called deuterium (with one proton and one neutron), but they didn't amount to much. As a result, going to heavier and more bound nuclei would have required either adding hydrogen to helium or helium to helium. The problem, though, is that there are no stable nuclei with five nucleons or eight nucleons (a nucleon is either a proton or a neutron). Therefore, any such combinations immediately split apart.

The result is that after this early phase, the only nuclei with significant abundance in the universe were ordinary hydrogen and ${}^4\text{He}$. We've already said that this is insufficient to form complex molecules. This says that life would have to wait until, somehow, heavier elements formed. So how does that happen? To determine this, we will now go over the essential role that stars play in producing elements heavier than helium, and how that matter gets out into the universe.

Production of elements heavier than helium

In contrast to the quick production of hydrogen and helium in just the first few minutes of the universe, other elements take a long time indeed. Stars are powered by nuclear fusion, in which light nuclei combine to make heavier nuclei. For most of their life, on the so-called "main sequence", stars fuse hydrogen into helium, so we wouldn't seem to be gaining much. However, near the end of their lives fusion can produce heavier elements such as carbon, nitrogen, oxygen, and eventually iron. Of course, there also has to be some way to get those elements out into space as opposed to keeping it all in the star, so let's talk both about how those elements are produced and how they get out.

First, it is useful to understand the fusion process a bit better. In the centers of stars, the matter is so hot and dense that true atoms don't exist; instead, the electrons move around freely and independently of the nuclei. Suppose that we have a core that is mainly hydrogen, which is the case for most of a star's life. Then the nuclei are individual protons. To get helium nuclei out of this, we must eventually convert four protons into two protons and two neutrons. It is so improbable that four protons all happen to hit at once and two convert that this never happens. Instead, there is a complicated sequence of collisions that build up lighter nuclei first and end up with helium.

When one has used up the hydrogen in the core of a star, then if the star is massive enough it contracts, heats up, and starts to fuse helium to carbon. Note that in the early

universe, we said that this didn't happen because there is no stable element that has eight nucleons. In a star, this is still true, but one can have two helium nuclei come together *temporarily*, then have a third helium nucleus hit while the first two are somewhat bound. This gives carbon-12, which is stable. Similarly, after the main supply of helium in the core has been used up, one can combine elements to get heavier and heavier nuclei. However, the amount of energy that one gets per mass in fusion reactions drops drastically after the H→He reaction, so the succeeding steps are much shorter than the main sequence. Indeed, once one gets up to iron and nickel, further fusion requires an *input* of energy rather than generating energy, so that's the end of the road. For most stars, actually, they never get to that stage; they simply burn hydrogen and then helium.

In principle, then, plenty of carbon and other heavier nuclei are produced in stars. However, stars are too hot for complex molecules to form, so we need to send out at least some of those heavier elements for life to have a chance.

For a low-mass main sequence star such as the Sun, not much gets out. The only way that matter can leave the Sun is by a solar wind, in which radiation from the Sun interacts strongly with some of the heavier elements and pushes them away. This, unfortunately for life, is but a tiny trickle. However, more massive stars are far brighter, so they push out mass at a high rate, up to a solar mass per hundred thousand years in some cases (lasting for maybe a million years). That's promising. Even the Sun and similar stars do their part because when they become red giants they are much brighter than on the main sequence, and a third or half their mass can eventually go out into the universe.

Really massive stars (those starting with at least eight times the mass of the Sun) have a more spectacular end. Rather than simply fading out after consuming their core helium, they burn heavier and heavier elements, eventually ending up with a rapidly growing lump of iron in their centers. This doesn't generate energy, and when it gets to about 1.5 times the mass of the Sun, it collapses suddenly. When it reaches the size of a city (10–15 km radius), it bounces and the shock thus produced blows the star to bits in a supernova. This distributes not just the elements up to iron, but everything beyond that as well, because there is plenty of loose energy to use to form things beyond iron.

Since these massive stars form rapidly and live but short lives, this all means that, in principle, as soon as the first massive stars have undergone supernovae, heavy elements are spread throughout the universe. In a given location in the universe when it was, say, 100 million years old it is possible that no stars had formed yet. However, it appears that by the time the universe was 1 billion years old, stars and galaxies were in full bloom everywhere.

From that standpoint, therefore, life in principle had the necessary raw materials no later than 1 billion years after the Big Bang. Our Solar System, in contrast, formed about 9 billion years after the Big Bang, and we have appeared 13.7 billion years after the Big

Bang. Could it be that there are lifeforms in the universe that are ~ 10 billion years older than we are? Some people feel that if a rocky planet such as Earth is necessary, there might have been another few billion years needed to get enough heavy elements to form planets. It is also possible that if the abundance of heavy elements was too small (say, $1/1000$ of what it is now), then life would have been too challenging to produce. This is one of the many questions that is still up in the air.