Components of life: the origin of the elements

Our course is a bit bold to talk about life in the universe, given that we only know about life on Earth. If we're not careful, it will be easy to slip into the way of thinking that what is critical for life *here* is critical for life *anywhere*. For example, must life originate on a planet the size of the Earth orbiting at our distance from a star very like the Sun, or can there be wide ranges from our situation?

In this lecture and the next, we'll try to go back to the basics. We will assert that for life to not only originate but also develop requires:

1. A long time. On Earth it took about three billion years to go from single-celled organisms to complex life. We don't know if that is slow, fast, or average. However, we can say that based on our observations of life around us, big changes in things large enough to interest us likely take at least millions of years.
2. Some kind of complex chemistry. Atoms found in all life on Earth include hydrogen, carbon, nitrogen, oxygen, phosphorus, and sulfur as the dominant components, with trace amounts of many other elements. Is this critical? We certainly don't know that every one of those is necessary. However, if we are limited to just hydrogen, or hydrogen and helium, our prospects don't look good (see below). We therefore assume that at a minimum we need elements heavier than helium.
3. A universe that is not completely uniform. A uniform universe contains nothing that would distinguish itself, so structures have to form somehow.

As we move through the course we will address some of these speculations in more depth. For example, on Earth, all life needs liquid water to go through its full biological cycle; that is, some microbes and spores can survive indefinitely when completely dry, but need liquid water to reproduce and grow. Is this a universal requirement? How about carbon; is its chemistry unique enough that it is essential to the formation of complex molecules?

Here, however, we give the cosmological background. In this lecture we will discuss what we know about the age of the universe, as well as the formation of light elements. In the next class we will talk about the role of gravity in bringing together matter that could form structures, as well as how elements heavier than helium are formed and dispersed throughout the universe.

The age of the universe

As we've discussed before, one of the awe-inspiring and yet confusing aspects of the universe is that the scales on which it operates are radically different from what we encounter in everyday life. The size range is amazing enough (over more than forty orders of magnitude!), but here we are focusing on time. The oldest person we've ever met is probably at most a few years over a century, and human civilization is at most 10,000 years old. With this in mind, how can we possibly determine that the universe itself is billions of years old?

Indeed, this is a good general category of questions: how can we measure things that are far outside our direct realm of experience? Generically, the answer tends to be that (1) we have a model for how things behave, and (2) this model has been extensively tested in many circumstances, always giving consistent answers, hence (3) when we extend this model to things we can't measure directly, and get the same answers from many different samples or observations, we believe those answers. The tapestry of science is full of such examples, a bit like puzzle pieces that fit snugly together.

Let's be less vague. One way that we can at least place a lower limit on the age of the universe comes from radioactive decay. We'll discuss this in more quantitative detail in another class, but as a start we can give the basic principles:

- Atoms are made out of electrons (which basically move around in the outskirts of the atoms), plus protons and neutrons (which are in a tight ball in the center, or nucleus, of the atom). The type of element (say, hydrogen, helium, lithium, etc.) depends only on the number of protons in the atom.
- Some nuclei are stable: leave them alone and they'll stay as they are indefinitely. Some, however, are unstable: eventually they will decay into another nucleus.
- The process of decay is entirely statistical, i.e., one can't predict with certainty when any given nucleus will decay. In addition, the probability of a decay in some small time Δt is completely independent of how long the nucleus has lived thus far.
- Typically, one talks about the "half-life" of a nucleus. For example, the half-life of ^{238}U (uranium, which always has 92 protons, has 146 neutrons in this isotope for a total of 238 neutrons plus protons) is about 4.5 billion years. The meaning of the half-life is that if you start out with a large number of uranium nuclei, say 2×10^{18}, then after 4.5 billion years you expect that half, or 10^{18}, have decayed. The statistical nature of the decay means that we can actually measure this in a lab that doesn't have 4.5 billion years to spare; specifically, after 4.5 years one expects a fraction (1/billion)x0.5 to have decayed, or 10^9. With large enough samples, one can measure the half-lives of many nuclei very precisely.
- Laboratory experiments show that even under extreme conditions of temperature, pressure, and so on, the half-life is highly stable. It can therefore act as an excellent clock: simply figure out the original amount of the nucleus, compare with the current amount, and voila!

There are some complexities in using this method to establish ages of things if you don't know the *original* abundance of the nucleus. However, there are clever ways of getting around this in a given sample if you have multiple measurements of the abundances of the "parent" nucleus (the original) as well as a couple of isotopes of the "daughter" element (the product of the decay). In particular, suppose that you have a parent nucleus P that decays into a daughter nucleus D (called a *radiogenic* nucleus, because it can be produced by radioactive decay). Also suppose that there is a different isotope D_i of the daughter element that is *not* produced by radioactive decay (and hence is *non-radiogenic*), so we assume that its concentration is constant. An example might be that the parent is ^{147}Sm, the radiogenic daughter is ^{143}Nd, and the non-radiogenic daughter is ^{144}Nd. By simple algebraic manipulation we find

$$\frac{D+\Delta P_t}{D_i} = \frac{\Delta P_t}{P-\Delta P_t}\left(\frac{P-\Delta P_t}{D_i}\right) + \frac{D}{D_i}\ . \tag{1}$$

Here D is the initial concentration of the radiogenic daughter element, D_i is the concentration of the non-radiogenic daughter element (which is constant with time), P is the initial concentration of the radioactive parent nucleus, and ΔP_t is the amount of the parent nucleus that has decayed in time t.

The point of this method is that the left side is the ratio of the *current* concentration of the radiogenic daughter to the non-radiogenic daughter, and the factor in parentheses on the right is the *current* concentration of the parent to the non-radiogenic daughter. Both are therefore measurable right now. If you have a rock of fixed age that has parts with different initial ratios of parent to radiogenic daughter, plotting these measurable quantities against each other now must produce a straight line. From the equation, you can see that the slope of this line depends only on the time elapsed. Therefore, you get an age and you also calibrate the method, because the degree to which the points do *not* fall on a line tells you about other effects that might have entered.

Use of these methods on meteorites indicates that the solar system is 4.55 billion years old, with an uncertainty of less than 100 million years, which is pretty good! We can therefore be confident that the universe is at least this old. How much farther back can we go?

One method uses our understanding of stellar evolution. We can only see a given star at one stage in its evolution, but since we have an effectively unlimited number of stars we get good sampling anyway. In addition, from the standpoint of their overall evolution stars are pretty simple objects: just balls of gas, basically. This means that by the middle of the 20th century people had a very good idea of how stars evolve. Basically, they spend most of their time fusing hydrogen into helium on the "main sequence", then a much shorter time going through the rest of their evolution until they become a stellar remnant (i.e., a white dwarf, neutron star, or black hole). In addition, the time they spend on the main sequence depends almost entirely on their initial mass.

Knowing this, we can look at a large, isolated group of stars that we think was formed all at the same time, and get its age by determining the highest-mass star that is still on the main sequence. The best candidates are the globular clusters, which are very old collections of hundreds of thousands of stars. The net result is that the oldest such collections appear to be 11–13 billion years old. This is reasonable: our Sun actually has a fair abundance of elements heavier than helium, and as we'll discuss below this implies that there had to be a few generations of stars formed before the Solar nebula started contracting.

Yet another independent method uses white dwarfs. These are the remnants of stars that start out with masses less than about eight times the mass of the Sun. Since these remnants don't undergo any fusion, they just sit there and cool. Models of the cooling aren't too bad to construct, and lead to white dwarf ages up to 12.1 ± 0.9 billion years.

The final independent model we'll discuss is the most precise for measuring the age of the universe as a whole. The standard cosmological model (more on this below) predicts that as the universe expanded it cooled off. About 380,000 years after the Big Bang, electrons and nuclei combined rather suddenly, meaning that the radiation that had previously been trapped could now sail through the whole universe to us. This is the cosmic microwave background. The background is very smooth and uniform, but not perfectly so; in fact, the various hot and cold spots carry very reliable information about the history of the universe, including its age. When combined with a host of other cosmological data, we find that the universe is about 13.7 billion years old. Note that this is consistent with all of our other measures. Life therefore, in principle, has billions of years to develop. How quickly could this have happened, though? Is it possible that life arose a thousand years after the Big Bang? A million? A billion? To answer this we need to think about the origin of elements.

The origin of elements

We'll start by thinking about what we really need for life. Some complexity would be good, 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 the building blocks of molecules, the atoms, have to be able to come together in long chains. We can approach this by assuming that we first 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 (like 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 bringing together protons and neutrons. For example, the most common isotope of helium (^{4}He) has two protons and two neutrons. This happened 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 ^{4}He. 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}He is by far the most bound of the light elements, so that (2) essentially only hydrogen and ^{4}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}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. That is the topic of our next lecture.