Last time we left off at hydrogen and helium, because that's all that formed for the first hundred million years of the universe except for dribbly little bits of lithium and beryllium. As this isn't enough to get complicated molecules, we must look elsewhere for the stuff of life. We'll do our searching in this lecture. Our first step will be to discuss the content of the universe and show how large structures form: galaxies and stars in particular. We will then go over the essential role that stars play in producing elements heavier than helium, and how that matter gets out into the universe. We will conclude by discussing the many organic molecules that are found in interstellar clouds and on other planets and moons, which suggest that the building blocks of life may actually be fairly common.

The content of the universe

If we agree that uniformly spread stuff isn't alive, we need some way to cause it to clump. Our understanding of how the clumping happens depends on the content of the universe, so let's survey that briefly.

As you probably know, in the past several years it has become clear that the stuff that we are made of is only a tiny fraction of the mass and energy in the universe. Even more disconcertingly, we don't have a good idea about what the rest is!

More specifically, it turns out that currently only about 4% of the total mass-energy content of the universe is in protons, neutrons, and electrons. 23% is in particles of an unknown type that barely interacts with matter. This is called "dark matter", and believe it or not we can actually rule out every single type of particle ever detected as a dark matter candidate! Many people hope that dark matter can eventually be detected in the laboratory (indeed, there is one group that claims they've already seen it), and in particular that it is something beyond the standard model of particle physics; there are theories suggesting that other types of particles are necessary.

How, though, can we infer that such stuff exists if we can't detect it directly? The way this has been done is through gravity. All mass-energy gravitates, so if there are dim but massive things around they can make their presence known. After all, this is the way that we detected the supermassive black hole in the center of the Galaxy.

One approach is to look at stellar orbits at various distances from the centers of galaxies. Of course, we don't wait around the requisite several hundred million years to see the orbit! Instead, observers take spectra of galaxies including our own, determine the line-of-sight speed from Doppler shifts, and then use Kepler's laws to estimate the mass contained inside the orbit of the star.

Starting in the late 1950s, Vera Rubin and others began to find that the rotation curves (i.e., orbital speed versus orbital radius) did *not* behave as expected. A spiral galaxy such as the Milky Way has widely distributed mass, but at the Sun's orbital radius and beyond the number density of stars is much less than it is further in. One therefore does not predict a rotation curve $v \propto r^{-1/2}$ as exists in the Solar System, where there is a single dominant mass. In fact, one expects that the rotation speed should *increase* with increasing radius in the inner ~ 1 kpc. However, the diminishing density at greater radii would be expected to lead to a gradually decreasing orbital speed.

This is not what is seen. Instead, the orbital speed of stars more or less flattens out, to a speed that is therefore called $v_{\rm flat}$. Most of the community interprets this as the result of matter we can't see (i.e., dark matter), but some think it might be because gravity itself is modified at low enough accelerations. I personally lean towards dark matter being real, but there is room for argument.

Even weirder, though, is that the rest of the universe, a full 73% currently, is something that is pushing the universe apart faster and faster! This has been labeled "dark energy" and may well be equivalent to Einstein's "cosmological constant" that he introduced in 1917 in a failed attempt to allow for a static universe. We *really* don't know what causes this. Fortunately for our discussion of structure formation, the importance of dark energy has only come up in the relatively recent history of the universe, as opposed to when the first stars and galaxies were forming. At those earlier epochs, dark energy could be ignored, so we'll drop it (whew!).

How structure forms

First of all, let's sharpen the structure formation question. Right now, there are some parts of the universe that are a lot denser than others. For example, you and I are a modest factor of 10^{30} times denser than an average part of the universe! It is that kind of structure formation that (as far as we know) is necessary for life.

However, in the early days the universe was really, really, uniform. For example, 380,000 years after the big bang (at the time that the cosmic microwave background started streaming freely), the deviations from uniformity were only at the few parts in 10^5 level. How did we get from there to here, and how long did it take?

Remarkably, gravity by itself does the initial job, followed by a little bit of electromagnetism. Since early on dark matter was the major component of the universe (dark energy was not yet important, and electrons/protons/neutrons were just about 1/6 of the total density of the dark matter), we have a relatively easy picture. Dark matter basically doesn't interact in any way except gravitationally, meaning that it is relatively easy to treat. What simulations and theory shows is that early on only small concentrations of dark matter can come together and stop expanding with the universe, but that these collections grow larger and larger as time goes on (until dark energy causes the expansion to accelerate, at which point no larger collections of matter come together).

From the standpoint of life, though, this is still unsatisfactory because dark matter just floats hither and yon, simply orbiting rather than forming complex structures. We therefore have to concentrate on what the ordinary matter is doing at this time.

First, recall that ordinary matter has only about 1/6 as much stuff as dark matter. Therefore, the ordinary matter follows where the dark matter goes, at least early on. The ordinary matter has some temperature, so for it to collect and stay in one spot requires that the gravitational potential in a dark matter concentration be enough to hold the matter in. This is thought to have happened first when the universe was maybe 1/200 of its current age, i.e., about 70 million years old.

When ordinary matter is comfortably settled in a collection of dark matter, then the ordinary matter can start to cool. When it does so, it falls closer to the center of the matter distribution; one of the results of this is that visible galaxies, such as our Milky Way, are concentrated in a much smaller volume than is occupied by the dark matter (say, 100,000 light years across versus 2 million light years across). In a similar way but on a much smaller scale, clouds of interstellar gas that are initially a few to tens of light years across and might contain hundreds to millions of solar masses contract, cool, fragment into stellar-mass clumps, and continue to contract and fall. The falling heats up the matter, and eventually, at high enough temperature and density, nuclear fusion sets in and a star is born. It is these stars that have taken the original hydrogen and helium and produced heavier elements, so let's discuss one of the coolest aspects of astronomy: as Carl Sagan said, we are literally made of star stuff.

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, and simply burn hydrogen and (for stars other than the least massive) 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 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? As we'll discuss in the next lecture, 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.

In the meantime, though, let's push through. We have argued that we need complex molecules in order to have the complexity necessary in life. Is this unique to the Earth, or do we have evidence of such molecules elsewhere?

Molecules in space

Before going over some of the molecules that have been detected, let's back up a bit and marvel at our ability to say anything about this at all! Indeed, the power of spectroscopy to inform us about compositions was so unexpected that in 1840 Augustus Comte used the composition of stars as an example of something that would never be known. However, precise measurements of absorption and emission lines has given us remarkably detailed information about stars and galaxies.

To detect molecules requires spectra that depend on their molecular form rather than the individual atoms that make up the molecules. That is, if we are simply looking at a normal transition of an electron, such a transition will be basically the same for a given atom whether or not it is in a molecule (not quite, but close). Therefore, the transitions that are studied are vibrational or rotational transitions. These are much lower energy than electronic transitions, so we observe them using radio waves. Large molecules themselves tend to be more fragile than small molecules, so typically one should look in cold, dense regions such as molecular clouds.

This has been an extremely productive enterprise. There are, of course, plenty of inorganic molecules. H_2 is the most common molecule, CO is seen easily, and SiO, OH, NaCl and many others have been observed. However, many organic molecules have been observed as well; indeed, more than 130 at last counting. For example, simple sugars have been found, as have different types of alcohol (followed by much drinking, I'm sure!). More impressively from the standpoint of life is that the simplest amino acid, glycine, has also been discovered in interstellar clouds. The fundamental role that amino acids play in life on Earth makes this interesting because it suggests that organic molecules, the building blocks of life, could well be common in the universe.

Summary

The conclusion of this lecture and the previous one is that the universe had to age a fair amount, between a hundred million and a billion years depending on the location, before heavy elements were present. We also find that when enough such elements are present, and cold, dense environments are available, many molecules form. Interstellar clouds, though, despite being dense by astronomical standards, are nearly perfect vacuums by terrestrial standards: maybe 10^{-13} of atmospheric pressure even for the cores of such clouds! We presume (and we take a bit of a leap here) that much greater condensation is needed for life. Now, it could be that somewhere around a distant star one can find life on a gas giant such as Jupiter. We really don't know. However, since we live on a rocky planet, we will in the next class discuss the formation of planets and in particular the terrestrials.