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. The basic principles are:

- 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; for example, after 4.5 years one expects a fraction (1/billion)x0.5 to have decayed, or 5×10^{-10}, which multiplied by our original population of 2×10^{18} gives 10^9 expected decays. 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 quantity 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, from, e.g., the Wikipedia page on isochron dating, suppose that we have an initial concentration P of the parent isotope, an initial concentration D of the daughter isotope (which could be present initially, or could be produced by the decay of the parent), and a concentration D_i of a non-radiogenic daughter isotope (i.e., this isotope of the same element as the daughter D does *not* come from radioactive decay). We assume that D_i is constant with time. Then if ΔP_t is the amount of the parent isotope that has decayed in a time t, algebraic manipulation yields

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

Note that the left hand side shows the *current* ratio of the radiogenic daughter to the non-radiogenic daughter, and the quantity in parentheses shows the *current* ratio of the parent to the non-radiogenic daughter. In addition, the factor in front of the parentheses is simply a measure of time: it is related to the fraction of the parent that has decayed, and because the half-life of the parent can be measured in a laboratory, this tells us its age. If many samples of the same age (e.g., in meteorites) produce a straight line when $(D+\Delta P_t)/D_i$ is plotted against $(P-\Delta P_t)/D_i$, then this indicates a self-consistency of the method. If it does not, something is wrong and the answer is therefore not reliable. As a specific example, we can consider a parent of ^{87}Rb, a radiogenic daughter of ^{87}Sr, and a non-radiogenic daughter of ^{86}Sr. Note that although ^{87}Rb has a half-life of 48.8 billion years (!), the mass fractions can be measured very accurately.

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 (this defines 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, so 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 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, which we do in the second supplement.