Observations of Light Element Abundances

Last time we discussed the expectations of Big Bang Nucleosynthesis (BBN to its friends). Here we talk about the observations. For a bit of change of pace, and to give some appreciation of the difficulties and the care needed, we're going to go the sausage-making route here: lots of gory details. In some cases, we will use the standard nomenclature that X is the mass fraction of hydrogen, Y is the mass fraction of helium, and Z is the combined mass fraction of everything else.

The Simplest Test: ^{4}He

As always, before we get into the details it is a good idea to do the broadest overall test we can. In this case, ^{4}He is the way to go. This is because although, as we said last time, the mass fraction should go up with increasing baryon fraction, the dependence is pretty weak. This means that the primordial ^{4}He mass fraction needs to be around 25% (recall that subsequent stellar evolution doesn't change this number much). If it were substantially different from this, then either some other major mechanism would be playing a role or BBN itself would be called into question.

The fraction does indeed turn out to be about 25%, so this is a fine broad-scale test of the model. However, merely stating it like this doesn't really give us a sense of what is involved. Therefore, **Ask class:** how would you go about an approximate estimate of the mass fraction of helium in the universe?

This is more complicated than it sounds. As a first step, you need to be confident that whatever you're observing has a representative helium fraction. For example, if you decided to figure out the helium mass fraction of the Earth, you'd get a very small number because Earth's gravity is insufficient to hold helium. Indeed, much of the helium on Earth exists because ongoing radioactive decay can produce helium nuclei. An indication of how rare helium is on Earth (in addition to its chemical standoffishness) is that it was actually discovered via spectral lines in the Sun, rather than on Earth.

A better attempt would thus be to look at the Sun. This contains almost all of the mass in the Solar System, and its escape speed is much larger than the speed of helium nuclei at the photospheric temperature of $T \approx 5,800$ K, so we might feel good that the helium pretty much stays put.

There are, however, additional issues. It is not obvious that the process of star formation necessarily funnels a representative amount of helium down to the center where the Sun forms (maybe a disproportionate fraction of hydrogen, or helium for that matter, gets blown away). It could also be that even if the fraction throughout the Sun is about the average for the universe, the fraction at the photosphere (which is what we can measure) is different. In addition, since we detect helium and other elements via their spectral lines, perhaps the details of the environment affect the production of these lines in such a way as to make helium appear more or less abundant than it really is.

Indeed, this last point is one that was first appreciated by Cecilia Payne-Gaposchkin in her 1925 Ph.D. thesis. The solar spectrum is dominated by lines from heavier elements (carbon, nitrogen, oxygen, iron, and many others). Prior to her work, astronomers such as Henry Norris Russell had asserted that the Sun must therefore be made primarily from these heavy elements.

Payne-Gaposchkin realized, however, that there is a major observational bias: we can only see lines if some electrons are left in the atom, but light elements such as hydrogen and (to a lesser extent) helium are easily ionized. In contrast, heavier elements have no problem hanging on to electrons in the photosphere. This implies that the strength of hydrogen lines in the solar spectrum is much weaker than would be indicated by its abundance. Payne-Gaposchkin's insight was that to get the abundances right one needs to do more than compare line strengths: one must also produce a self-consistent model of the atmosphere including the ionization fractions. Naturally, as a woman, she was put down for the statement that the Sun was mainly hydrogen and helium, but with hindsight she is recognized as having made an extraordinarily important contribution.

With all this said, even to get a rough value of Y from stars one needs to do careful atmospheric analysis. This can be done for many stars, and a consistent value of $Y \sim 0.25$ emerges. One can also look at gas clouds near and far, to establish whether this is truly a universal mass fraction. In all cases, though, since the actual measurements are of line strengths, it is necessary to have an accurate ionization model as well as good laboratory measurements of the intrinsic atomic physics parameters.

In the interest of being greedy, though, we're not satisfied with this approximate agreement with BBN. However, although the insensitivity of Y to baryon fraction is an advantage when one wants to do rough comparisons, it is a weakness when one wants precision. We now describe how such precision is pursued for helium.

More precise ^{4}He measurements

For this part we use as our prime reference Peimbert, M., Luridiana, V., & Peimbert, A. 2007, ApJ, 666, 636. To give the answer in advance, they find $Y = 0.2477 \pm 0.0029$, which is an increase of 0.0086 from their previous best value. The main reason for the increase has to do with new laboratory measurements of atomic recombination and excitation coefficients, but we'll get to that.

First, note that if we're trying to get precision instead of a rough value, our task is a lot more involved. For example, now we can't just pick any old star or gas cloud and measure its helium mass fraction. After all, though stars haven't made *much* helium, they've made some, and that would qualify as a contaminant. What should we do?

The basic idea is that the pre-star universe contained essentially nothing heavier than lithium, so we would like to be able to extrapolate back to that pristine composition. Therefore, it is common to do a large number of measurements of gas clouds with different metallicity, figure out Y in each case, and use dY/dZ to estimate the primordial composition. Peimbert et al. use the abundance of oxygen for this purpose. They then go on to discuss a remarkable set of potential issues and their estimated contribution to the uncertainty in the measurement of Y_p (here the p subscript means "primordial"). The list, with estimated errors and an indication of whether they are statistical or systematic:

1. Collisional excitation of HI lines (±0.0015 systematic)
2. Temperature structure (±0.0010 statistical)
3. O(dY/dO) correction (±0.0010 systematic)
4. Recombination coefficients of the He I lines (±0.0010 systematic)
5. Collisional excitation of the He I lines (±0.0007 statistical)
6. Underlying absorption in the He I lines (±0.0007 statistical)
7. Reddening correction (±0.0007 systematic)
8. Recombination coefficients of the HI lines (±0.0005 systematic)
9. Underlying absorption in the HI lines (±0.0005 statistical)
10. Helium ionization correction factor (±0.0005 statistical)
11. Density structure (±0.0005 statistical)
12. Optical depth of the He I triplet lines (±0.0005 statistical)
13. He I and H I line intensities (±0.0005 statistical)

Looking at this we see that some of these are related to fundamental atomic physics (numbers 4, 8, and 10), some have to do with level populations in the environment, such as collisions (numbers 1, 5, 6, and 9), some have to do with the measurements themselves (numbers 7, 12, and 13), some relate to the properties of gas clouds (numbers 2 and 11), and then there is the extrapolation to zero metallicity (number 3). We also see that all of these uncertainties are within a factor of three of each other, which unfortunately means that it's not as if dramatic improvement in any single one of them will dramatically improve the overall determination of Y_p.

Implications for baryon fraction from ^{4}He

Based on Y_p we can use BBN theory to estimate the baryon density as a fraction of critical, Ω_b. Actually, it turns out that uncertainties in Ω_b are degenerate with those for the Hubble parameter, so usually one sees quotes for $\Omega_b h^2$, where $h \equiv H_0/100$ km s^{-1} Mpc^{-1}. Peimbert et al. find $\Omega_b h^2 = 0.02122 \pm 0.00663$, which for $h = 0.72$ means $\Omega_b = 0.04$.

Deuterium abundances

^{4}He is very common, so its lines are easily measured. In addition, ^{4}He is difficult to destroy and relatively little is created, so it is a robust nucleus. On the other hand, as we've seen, its abundance is pretty insensitive to Ω_b.

Deuterium is the opposite in many ways. It is a comparatively weakly bound nucleus, hence is easily destroyed. On the positive side, this means that it is highly sensitive to Ω_b. On the negative side, it is much tougher to observe (because there isn't much of it!), and it can be chewed up pretty badly in stars.

With this in mind, we now follow O'Meara et al. (2006, ApJ, 649, L61) in their determination of the D/H ratio and its implications. The general approach is to look at the spectra of quasars. Between the quasars and us one sometimes finds absorption line complexes that come from intervening gas clouds (see Figure 1 for an example of some spectra). These clouds tend to be far away from active star formation, so they have a decent claim to be primordial. Incidentally, such systems have also been analyzed to provide information on structure formation. However, as O'Meara et al. point out, for good analyses of the D/H ratio there are multiple criteria to be satisfied:

- The amount of hydrogen in the cloud has to be pretty large. Since the typical D/H ratio is only about 10^{-5}, you need a lot of ordinary hydrogen to get enough deuterium to detect.
- The velocity structure of the gas has to be simple, and ideally you would like either just one comoving bit of gas or, if there are multiple absorption complexes, for them to be well separated. The reason is that hydrogen and deuterium have almost the same spectra, because what matters is the reduced mass and this is almost the same for both. In velocity space, the Lyman lines of deuterium are offset by only 82 km s^{-1} from hydrogen. Therefore, any greater intrinsic velocity spread will confuse matters.
- There cannot be other interloping line structure, including metal lines.
- The background quasar must be bright, otherwise the weak D lines are not straightforward to characterize.

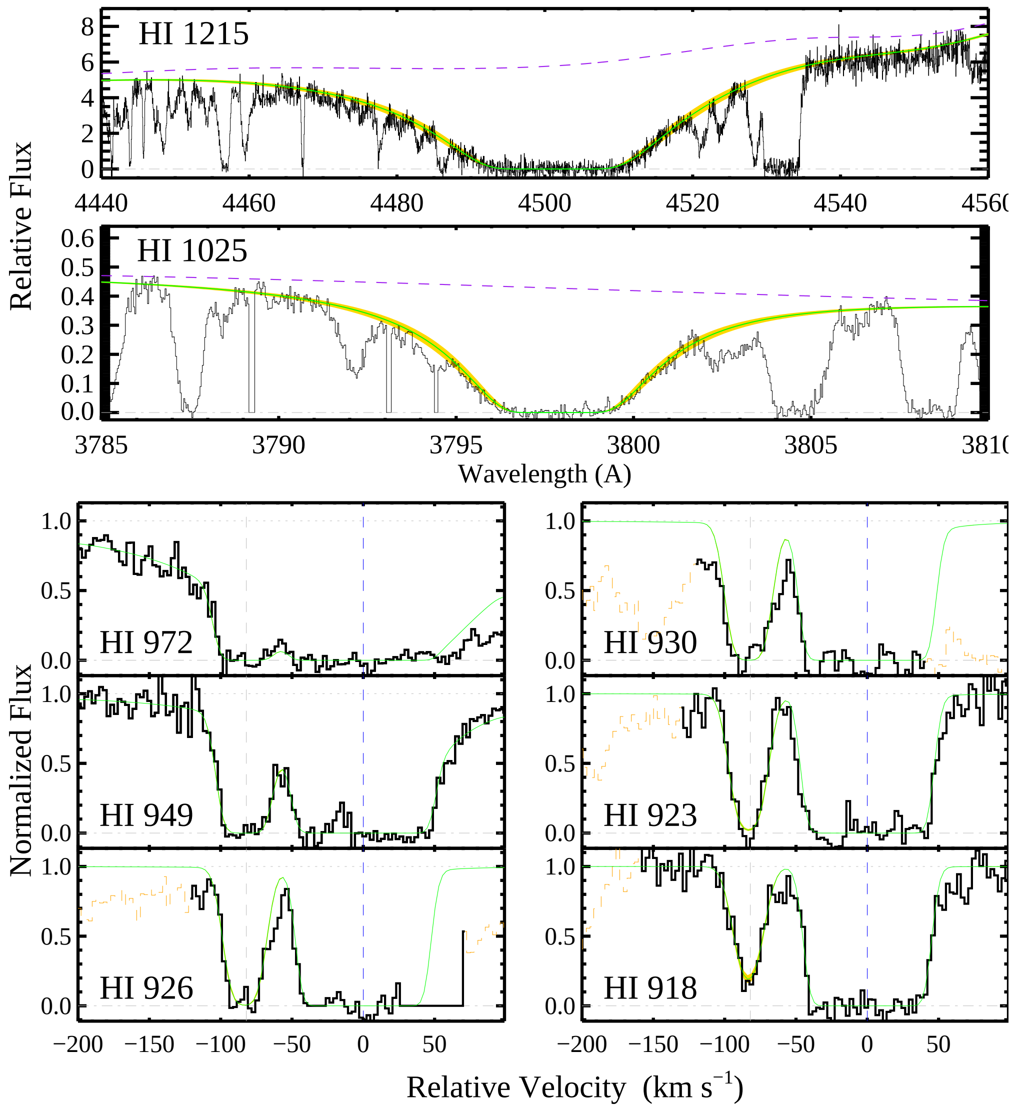

Fig. 1.— Hydrogen and deuterium lines from absorptive material along the line of sight to a quasar. This is Figure 1 from O'Meara et al. 2006, ApJ, 649, L61

The net result is that only about 1% of quasars at $z = 3$ are suitable for this purpose. O'Meara et al. analyze one such quasar, and find that the D/H ratio is $\log_{10}(\mathrm{D/H}) = -4.48 \pm 0.06$. Converting this into a baryon density then involves some uncertainty in the nuclear reaction rates as well as the measurement itself. The final answer is that $\Omega_b h^2 = 0.0213 \pm 0.0014$. This is entirely consistent with the value inferred from ^{4}He above. Both of these are then consistent with the inference from the third-year WMAP data: $\Omega_b h^2 = \Omega_b h^2 = 0.0223 \pm 0.0008$.

Where do we stand? In many ways, BBN is extremely successful. The agreement between inferred Ω_b from helium, deuterium, and WMAP is really impressive (although if you're a cynic you wonder whether abundance measurements have been influenced by WMAP). Given that alone, you'd have to say that the idea of a hot dense universe has been a rousing success. Still, some discrepancies remain. ^{7}Li also has an abundance predicted by BBN, yet measurements of the atmospheres of very metal-poor stars consistently find values 2-3 times lower than predicted. Is this a crisis? The current feeling appears to be no: basically, the problem is that diffusion of elements and destruction of lithium are uncertain enough that perhaps this is all consistent. It is, nonetheless, something to track as observations improve.

Intuition Builder

We discussed worries of deuterium destruction, but what about the production of deuterium? Could it be that active star forming regions or quasars produce significant deuterium and that this contaminates the measured regions?