Comments on Assignment 4

Question 1: Primordial deuterium

a) The designation `baryometer' comes NOT from the combination of
the two ideas that:

(i) the Big Bang (BB) is the only source of D and
(ii) D is thoroughly destroyed and never synthesized by stars. Rather, D is a baryometer because the yield from the BB decreases with increasing η (= baryon/photon ratio).

The temperature-time profile of the BB is independent of η. At early times, the D/H ratio is near-equilibrium -- very very low - because photodisintegration of D occurs at a high rate. The low D/H acts as an effective bottleneck on nucleosynthesis beyond D.

The resultant yield of D involves two-body reactions with D obviously (I hope!) and these destruction reactions are more effective the higher the density of baryons (the higher η) and this reduces the surviving D abundance --- hence, primordial D/H is a baryometer for the BB.

b) Descriptions of D/H determinations from QSO spectra were generally too concise for someone new to the topic to obtain a clear idea of what is involved.

Here are key points:

i) The isotopic shift between a Lyman line of H and the same line of D is 82 km/s with the D line to shorter wavelengths. This arises from the difference in reduced masses and applies to all H-D lines.

ii) Obviously, if Lyman lines are to be observed with optical high-resolution spectrographs, the QSOs must be of high redshift. (Were a high-resolution ultraviolet spectrograph available on a suitably large telescope, would you opt to use it and why?)

iii) The absorption spectrum of a QSO is produced by gas along the line of sight to the QSO. It is VITAL that the foreground gas have a sufficient column density of H I that D I lines are detectable and that its velocity structure be simple and, in particular, that a weak H I cloud not occur at 82 km/s from a principal cloud. A pretty good idea of the cloud structure is provided by profiles of metal lines longward of the Ly α emission.

Pagel (Figure 4.5) shows one fit of a H-D profile - a fit to a Lyman α profile. This is not a typical situation. Rather look at the Cooke et al. (2014) paper and their Figure 3 to see which D Lyman
lines are resolved and for full details on their extraction of the H and D column densities.

c) Their D I line was, I think, shown to be a H I `interloper' and then or subsequently it was realized too that the Songaila et al. D/H was much higher than other QSO determinations.

d) See Cooke et al. (2014). But the efforts to measure D/H will continue such is the allure of the Big Bang.

Question 2. Primordial lithium (No answers!)

Analyses of the absorption line spectrum of QSOs show lines of quite a few ions from quite a few elements, Why not Li?

First, Li has to be detected via its neutral atom and the resonance doublet at 6707A. Li+ is He-like and Li++ is H-like, both with resonance lines in the far-uv and in the Lyman forest. For example, the Li++ resonance lines equivalent to H Ly alpha is at 1215/9 = 135A. Undetectable!

The Li atom's resonance lines will be red-shifted into the infrared for the high-z QSOs used for setting abundances of deuterium and metals.

Second, the Li atom has a low ionization potential and thus is ionized in the ambient radiation field of the QSO and the IGM. One has to make a large (uncertain) correction for this ionization.

Li has a low abundance but so does Zn which is often detected as Zn II. So abundance itself may not be fatal, but correcting for ionization will be key.

Finally, one needs to estimate the minimum detectable equivalent width for a high-resolution spectrograph on a large telescope.

Question 3. Big-Bang nucleosynthesis and reaction rates

a) The contention is often made that predictions of BB nucleosynthesis are not limited greatly in accuracy because of uncertain nuclear reaction rates. Or alternatively, one can read that the necessary rates have all been measured at the energies prevailing in the brief period of BB nucleosynthesis. True!

Part a was an exercise in estimating the Gamow peak and the width of the Gamow window. See Pagel or Iliadis (eqns. 3.77 and 3.81).

Then, look at the diagrams in the NACRE websites showing the experimental data in the form of S(E) versus E and see that the Gamow peak/window is within the E range of the measurements.

b) The neutron's half-life affects the yield of ^{4}He in two ways.

First, the half-life is a measure of the strength of the weak interaction which through the time of neutrino decoupling sets the value of the n/p ratio at neutrino decoupling. The longer the half-life the weaker the weak interaction, the earlier the decoupling and the higher the temperature and the higher the n/p ratio. More n means more ^{4}He.

Second, there is a time delay between neutrino decoupling and the onset of nucleosynthesis. A longer n half-life increases this time interval but the longer n half-life offsets this increase somewhat.

The effect of the neutron half-life on the ^{4}He yield was first recognized by Tayler (1968, #Nature, 217, 433). Numerical evaluations can be found in various places: a 2 second change in the half-life corresponds to a change in Y of 0.0004.

c) The rate of expansion of the BB depends on the number of different types of relativistic particles. A faster rate of expansion leads necessarily to neutrino decoupling at a higher temperature and a higher initial n/p ratio.

The final ^{4}He abundance increases with increasing number of neutrino families. The change in Y is about 0.012(N(nu) - 3). See Steigman (2012, astro-ph 1208.0032) for a recent discussion.

The dependence of the He abundance on the number of neutrino families was noted first by Hoyle & Tayler (1964) in their Nature paper on the helium abundance. Pundits then noted that ``At the time when the first big bang predictions were made the upper limit to the number of neutrino families from particle physics was in the thousands''. Thus, observational inferences about the BB He yield were used to constrain an important piece of particle physics. Now, astronomy and particel physics agree that there are three families of neutrinos.

Question 4. The Lithium problem.

a) Now that WMAP/PLANCK satellites have mapped the cosmic microwave background very thoroughly, the CMB power spectrum provides a precise determination of the baryon to photon ratio, which is the one cosmological parameter determining the yields of the nucleosynthesis products from the Big Bang.

Figure 4.3 (Pagel) shows these yields. The shaded grey vertical stripe shows the CMB η from WMAP. (PLANCK gives a very similar value.) The horizontal hatched are in the ^{7}Li panel shows the Li/H abundance from the so-called Spite plateau defined by Li abundance measurements in warm metal-poor dwarfs (see Pagel Sec. 4.8 and Figure 4.12.) There is roughly a factor of 3 mismatch between the WMAP/PLANCK predicted Li abundance and that reported for the Spite plateau. This is the `Lithium problem'.

b) The stars on the Spite plateau are all old - say at least 10 Gyr. This encourages suspicions that lithium may have been destroyed since the stars were formed or it may have diffused down into the interior and out of the thin layer that is the atmosphere (and then destroyed by `warm' protons). Destruction may be driven by rotationally-induced currents etc. - recall the in-class discussion of the Sun's lithium abundance which is 30 times below the meteoritic value (= the Sun's initial Li abundance) -- See Carlos et al. (2016, A&A 587, 100) where several destruction mechanisms were tested on a sample of solar twins. And the Sun is only 4.6 Gyr old.

A counter argument is centered on the observation that the Spite plateau for warm dwarfs is very thin, apart from a few very Li-poor stars. This observation that stars on the plateau share the same Li abundance to a high degree seems counter to most, if not all, hypotheses invoking destruction/diffusion. For example, rotationally induced mixing surely varies from star to star depending on the rotation rate.

Perhaps, the leading hypothesis is that Li diffuses out of the atmosphere, as do other elements. When a star leaves the main sequence, it develops a convective envelope. This envelope grows as the star evolves to and up the red giant branch. This development mixes the atmosphere and the convective envelope and composition of the surface is restored to its initial value as effects of diffusion are erased. Lithium may not be completely restored because some Li may have been destroyed at the base of the convective envelope or by mixing to even deeper levels.

In class, we discussed how globular clusters have been studied from the main sequence turn-off to well along the giant branch. These abundance studies show (at least, claim to show) how metals such as Ca and Fe have higher abundances in giants as the diffusion is negated. Then, the diffusion corrected Li abundance is raised to a level close to the Big Bang value but I believe, still a little less than it.

The latest such investigation of a globular cluster is for M30 – see astro-ph/1603.01565, which is listed, as paper VI in a series. In a hurry? Then, look at Figures 4 and 6 and note the inferred initial Li abundance is still 0.15 dex less than the BB prediction.

c) See brief notes in Lecture 13. A non-standard Big Bang may invoke -- a change of cosmological model; a departure from the standard model of particle physics; or deficiencies in the nuclear physics ingredients contributing to the yields of 7Li AND other BB products.

Given the success of standard BB is accounting for the inferred primordial abundances of D, ^{3}He and ^{4}He, it is a requirement that changes designed to solve the Li problem not create new problems for other nuclides. I would say that deuterium presents the stiffest challenge in this regard; D/H is now well determined for gas close to pure post-BB gas.