Cosmic Deuterium and Baryon Density

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Abstract.
Quasar absorption lines now permit a direct probe of deuterium abundances in primordial material, with the best current estimate \((D/H) = 1.9 \pm 0.4 \times 10^{-4}\). If this is the universal primordial abundance \((D/H)_p\), Standard Big Bang Nucleosynthesis yields an estimate of the mean cosmic density of baryons, \(\eta_{10} = 1.7 \pm 0.2\) or \(\Omega_b h^2 = 6.2 \pm 0.8 \times 10^{-3}\), leading to SBBN predictions in excellent agreement with estimates of primordial abundances of helium-4 and lithium-7. Lower values of \((D/H)_p\) derived from Galactic chemical evolution models may instead be a sign of destruction of deuterium and helium-3 in stars. The inferred baryon density is compared with known baryons in stars and neutral gas; about two thirds of the baryons are in some still-unobserved form such as ionized gas or compact objects. Galaxy dynamical mass estimates reveal the need for primarily nonbaryonic dark matter in galaxy halos. Galaxy cluster dynamics imply that the total density of this dark matter, while twenty or more times the baryon density, is still well below the critical value, unless both baryons and galaxies are concentrated in galaxy clusters relative to the dark matter.

1. Introduction

The mere presence of deuterium in the universe confirms the conceptual framework of the Hot Big Bang, since unlike other primordial nuclei there is no other known source. Deuterium is the unique relic of the Big Bang: the total history of its cosmic production is over in only a few minutes, followed by billions of years of slow destruction in stars. Because it is relatively sensitive to the baryon/photon ratio \(\eta \equiv 10^{-10} \eta_{10}\), the primordial deuterium abundance is also the best way of measuring the amount of matter in the universe.

Until recently, deuterium was only measured within our highly chemically evolved Galaxy, which has destroyed a large but uncertain fraction of its initial deuterium. Measurements of deuterium abundance in QSO absorbers now allow a much more direct estimate of primordial abundance, in pristine material that has suffered little stellar processing. The Big Bang prediction is approximately fitted by

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(D/H)_p \approx 4.6 \times 10^{-4} \eta_{10}^{-5/3} = 1.9 \times 10^{-4} (\eta_{10}/1.70)^{-5/3},
\]
so an estimate of primordial D/H with an absolute accuracy of ±20% yields an estimate of primordial baryon/photon ratio accurate to ±12%, a very good precision by the standards of cosmic bookkeeping. This accuracy is attainable from measurements in QSO absorption line systems. I survey here the strengths and limitations of the QSO technique, compare early QSO results with Galactic estimates of \((D/H)_p\), and summarize cosmological implications of the low value of baryon density estimated from the high \((D/H)_p\).

2. Deuterium in Quasar Absorbers

Certainly in the long run, and I argue here even at the present, the best way to measure primordial D/H is through absorption lines of distant quasars. The principles are discussed by Jenkins in this volume. Profiles of the Lyman series lines of HI and DI and the Lyman limit optical depth combine to give good absolute column densities for both species in many situations, which in principle yield an absolute abundance almost free of ionization, temperature or density corrections in atomic gas. Accurate absolute column density information comes from optically thin or damped absorption lines of each species, and from the Lyman limit; ionization and recombination processes are nearly identical for both, so little detailed physical or geometrical modeling is required. Metal lines from the same clouds provide an independent measure of the amount of chemical processing, and in some cases the metal abundances are so small that significant deuterium depletion can essentially be ruled out. Eventually, many clouds will be measured along different lines of sight, testing the universality of the abundance in different places all over our past light cone, confirming (or not) that the past worldlines of matter were similar over an enormous spacetime volume, testing both the large scale homogeneity of spacetime (the “Cosmological Principle”) and the small scale homogeneity of matter.

The greatest weakness with the QSO technique is the ambiguity caused by the unknown distribution of material in velocity, or the problem of interlopers—clouds of hydrogen gas which happen by chance to lie at the redshift expected for deuterium associated with some other hydrogen cloud. Nature does not provide us with a system cleanly arranged in velocity, so any detection of deuterium must be regarded as suspect until this possibility is dealt with.

The first way to deal with interlopers is by seeking those relatively rare narrow-line systems where the turbulent component of linewidth is small and thermal width itself is also small, close to the minimum temperature consistent with photoionization heating. Because deuterium is heavier, the Doppler parameter \(b \equiv \sqrt{\frac{2kT}{m}}\) is smaller; in a purely thermally broadened profile, \(b = 13T_4^{1/2}\) for hydrogen, but only \(9T_4^{1/2}\) for deuterium. Gas under equilibrium conditions in these Lyman Limit absorbers is not expected to be cooler than \(10^4\) K (usually, \(T_4 = T/10^4\) \(K \approx 1\) to 3, over a very wide range for the ionization parameter; see Donahue and Shull, 1991), so lines with \(b \leq 10\) are unlikely to be hydrogen.

The accuracy of the fitting formula is about 7% in this range, which is almost as good as the estimated theoretical error (Krauss and Kernan 1995). Note that the conversion to a physical density also requires a knowledge of CBR temperature: \(\Omega_b h^2 = 3.631 \times 10^{-3} \eta_0 T_4^{0.726}\).

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interlopers. The ratio of the fitted Doppler parameter for D candidates to that of their H counterparts is also an important clue. Turbulent broadening tends to give both lines the same profile (so different shapes are not always expected), but a situation where the deuterium line is narrower than the hydrogen by a factor between $1/\sqrt{2}$ and 1 is again unlikely to be an interloper. Rugers and Hogan (1995) argue that the candidate deuterium absorber in Q0014+813 in fact displays both of these signatures of real deuterium, and so is likely to be a real measurement of D/H. It yields an abundance estimate $D/H = 1.9 \pm 0.4 \times 10^{-4}$ (Songaila et al 1994, Carswell et al 1994, Rugers and Hogan 1996 and this volume).

The errors in this estimate are real measured errors, in the sense that they reflect the total uncertainty in the fitted column densities, including ambiguities in Doppler parameter and velocity. They do not include systematic “model errors”, the most extreme example being a hydrogen interloper, and for this reason it is risky to rely on only one example, however clean. Also, one should bear in mind that although these are true “1σ” statistical uncertainties, the distribution of allowed values is highly nongaussian, so we do not have a good estimate of the probability of larger 2σ excursions from the fitted values. The ranges quoted throughout must be taken only as current best guesses, with the possibility of large departures not well constrained. This is main reason why more clean absorbers are urgently required.

Unfortunately clean conditions are not the rule. One can invoke statistical arguments based on larger samples of less trustworthy candidates— is there a statistical excess of lines at 82 km/sec to the blue of hydrogen (either relative to the red or relative to adjacent velocities)? Is there a statistical tendency of fits to improve with deuterium? There are several examples where this is the case, but so far the samples are not large enough to make statistical tests meaningful, although the dozen or so absorbers in two spectra we have studied so far indicate that that within the large errors the data are consistent with a universal abundance of the order of $10^{-4}$. The most trustworthy system to make a measurement remains the pair of absorbers in Q0014+813.

We now make a major leap of reasoning, and take the Q0014 measurement as an estimate of the primordial abundance. The justifications for this leap are (1) The Big Bang is the only known source of this deuterium, so any measurement is a reasonable lower limit on $(D/H)_p$; (2) The Q0014 cloud is extremely metal-poor and is unlikely to have cycled an appreciable fraction of its material through stars (that is, $D$ destruction by stellar cycling should be accompanied by noticeable enrichment), so it gives a reasonable upper limit on $(D/H)_p$; (3) Although it is only one site, it is still the best one we have at this writing— the most accurately measured and most pristine. For this value of $(D/H)_p$, Big Bang nucleosynthesis implies $\eta_{10} = 1.7 \pm 0.2$, which gives excellent concordance of Big Bang predictions with with the most straightforward interpretations of

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2One possible counterexample with $D/H \approx 2 \times 10^{-5}$ may have been found by Tytler and Fan (1994) on the line of sight to Q1937-1009. Carswell (1995) quotes a lower limit in a system in Q0420-388 of $D/H \geq 2 \times 10^{-5}$, with a best guess of $2 \times 10^{-4}$. Songaila and Cowie have a good fit for $2 \times 10^{-4}$ in Q0956+122. See the contribution by Rugers and Hogan in this volume for another example in GC0636+68, which yields $\log(D/H) = -3.95 \pm 0.54$. 

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helium-4 and lithium-7 abundance data (Copi et al 1995ab, Hata et al 1995, and Schramm and Steigman, this volume.) This gives us the confidence to trust in the Big Bang picture enough to use $D/H$ as a probe of cosmic baryon density.

3. Deuterium in Galactic Chemical Evolution

The value $(D/H)_p = 2.0 \pm 0.4 \times 10^{-4}$ is surprisingly high. Smaller values have previously been quoted as upper limits on $(D/H)_p$, giving lower limits on $\Omega_b h^2$, based on abundances in our Galaxy, together with the assumption that the sum $(D + ^3\text{He})/H$ cannot decrease.

In the Galaxy today, the deuterium abundance is less than $2 \times 10^{-5}$ (Linsky et al 1993, 1995, and Lemoine, this volume). This can be understood if the interstellar gas has almost all been processed through at least the outer envelopes of stars. A high primordial value $(D/H)_p \geq 10^{-4}$ requires that stellar processing in the Galaxy destroys not only deuterium but also its principal burning product, helium-3, in order to agree with the low values of this isotope found for the presolar material: analysis of the solar wind and meteorites reveals that the presolar nebula had about $^3\text{He}/H \approx 1.5 \pm 0.5 \times 10^{-5}$, $D/H \approx 2.7 \pm 2 \times 10^{-5}$, and $(D + ^3\text{He})/H \approx 4 \pm 2 \times 10^{-5}$ (Copi et al 1995ab, Hata et al 1995). It is probably necessary to have some helium-3 destructive mechanism also in order to explain the interstellar observations of helium-3, which are highly variable and sometimes very low, of the order of $0.6 - 6 \times 10^{-5}$ (Balser et al 1994; Wilson and Rood 1994).

While deuterium is destroyed by stars even before they enter the main sequence, and there is no doubt that helium-4 increases due to stellar processing, helium-3 is both created and destroyed by stars. It is fairly abundant in the interiors of main sequence stars in the temperature range of H burning, but is destroyed at higher temperatures. The helium-3 ejected back into the ISM when a star dies depends in detail on what the material of the star does after it leaves the main sequence and before it throws off its hydrogen envelope. Although the nuclear physics is well understood, details of the movement of material between different temperatures, and how it is ejected into the interstellar medium, are murky.

In galactic chemical evolution models, low mass stars (one or two solar masses) dominate stellar cycling and destroy the bulk of the pregalactic deuterium, so it is these stars that must destroy the helium-3 (Galli et al 1995, Olive et al 1996). There is a way this could happen: if the material in the stellar envelope on the giant branch is brought to high temperature ($1.5 \times 10^7 \text{K}$ or so) before it is ejected, the helium-3 would be destroyed. There is evidence for just such a process (“Giant Branch Mixing”, “Cool Bottom Processing” or “extra-mixing”; Hogan 1995, Wasserburg et al 1995, Charbonnel 1995)— from the change in C and N isotopic composition as stars leave the main sequence, from O isotope mixtures in meteorites, and from the continued decrease in lithium after cool giants leave the main sequence. There is thus at least a plausible way the helium-3 could be destroyed. Charbonnel (1995) has recently shown a detailed model which destroys helium-3 between 1 and 2 solar masses, but not above 2— thereby plausibly explaining the above facts. The three nearby planetary nebulae which have very high helium-3 (indeed, so high that they must
be atypical; Wilson and Rood 1992) could simply have progenitor masses above 2 solar masses. Although we do not have a clear constraint on the integrated stellar population ejecta, it is clearly not safe to assume that the Galaxy cannot reduce its helium-3 abundance with time. This is why the QSO measurements, even in their present unsettled state, are a more reliable measure of primordial $D/H$ than extrapolating from present Galactic values.

4. Cosmic Baryon Inventory

The inventory of things which must be made of baryons includes HI absorbers ($\Omega h \geq 0.003$, Wolfe 1993), galactic stars ($\Omega \approx 0.002$), and cluster gas ($\Omega h^{0.5} \approx 0.001$) (Persic and Salucci 1992), with errors on these quantities typically $\pm 30\%$. Elliptical and spiral galaxies contribute about equally to the stellar mass, although spirals are more numerous and with their younger populations dominate the blue and visible light by about a factor of two (Schechter and Dressler 1987). In addition there is an ionized gas component, including for example the Ly$\alpha$ forest clouds, whose density could be larger than all of these or smaller than any of them. The HI gas density is only this large at high redshift (that is, it might convert into stars at low redshift), so the minimum requirement is to count things at only one redshift. Taking $h = 0.75$, it could be that all known baryonic things could be accounted for with as little as $\Omega_b \approx 0.004$. The deuterium estimate of $\Omega_b = 0.011$ thus provides amply sufficient baryons to make all the things that need to be made of baryons. There must still be some unaccounted baryons, probably in the form of ionized gas and/or compact objects (Carr 1994). The baryon to galaxy mass ratio is about 5, and the baryon to (galaxy+known gas) ratio is about 3. Thus within the errors, the uncounted baryons could comprise up to, but probably not more than about twice that already seen. This is quite different from the previous situation, where lower estimates of $(D/H)_p$ required more than 90% of the baryons to be dark or in an ionized IGM. It leads to a tidy model of galaxy formation, which accounts for most of the facts about galaxies and QSO absorbers from $z = 0$ to $z = 3$, where baryons reside for the most part in gas, stars and compact objects in the vicinity of galaxies today (Fukugita et al 1996). The abundance of MACHOs in the Galactic halo (Alcock et al. 1995) is consistent with such a low density of baryons.

5. Nonbaryonic Dark Matter in Galaxies

On the other hand the estimated baryon density is not enough to account for the known dark matter in the universe. This problem is well known, although the need for nonbaryonic dark matter is greater than before, and now extends even to galactic halos.

Using the observed integrated blue luminosity density of galaxies, $L_B = 1.93^{+0.8}_{-0.6} \times 10^8 h$ solar units per Mpc$^3$ (Efstathiou et al. 1988), we can write the physical baryon density estimate as a global baryon mass density to blue luminosity density ratio, $\rho_b/L_B \approx 9h^{-1}$ in solar units. For our Galaxy, the mass to blue light ratio is about 60 if the mass is $10^{12}$ solar masses (Binney and Tremaine 1987), a typical dynamical estimate (Zaritsky et al 1993, Peebles
The mass to light ratio from galaxy rotation curves is often inferred in typical spirals—the same types that dominate the luminosity density—to be at least $30h^3$ (Rubin 1993). If this ratio is universal for galaxies, the global density of galactic dark matter is $\Omega \geq 0.02$.

Galactic dark matter is thus probably not made mostly of baryons—a stronger statement about nonbaryonic dark matter than was possible with the earlier higher baryon density estimates.

6. Global Dark Matter Density

The need for nonbaryonic dark matter is much greater if rich galaxy clusters, with dynamical mass to galaxy light ratios of about $300h^3$, fairly represent the global $M/L$, implying $\Omega \approx 0.2$ (Binney and Tremaine 1987). It is possible however that galaxy formation is more or less efficient in clusters than in the field, so that their $M/L$ is not the universal one. The appeal to greater efficiency is necessary especially in models with an overall dark matter density close to $\Omega = 1$.

Physical models of this “biasing” are constrained by the fact that the baryon to galaxy ratio in clusters, as measured directly, is close to its global value, as inferred from nucleosynthesis. White et al. (1993) estimate for example that the Coma cluster has a ratio of baryons to dark matter within the virial radius of $(0.05 \pm 0.01)h^{-1.5}$ in the form of gas, and $0.009 \pm 0.002$ in the form of stars; the higher baryon to galaxy mass ratio of 8 (for $h = .75$, compared to the above global estimate of 5) indicates if anything that galaxy formation was less efficient there than in the field, unless the gas mass is overestimated. This point does not depend on estimates of cluster mass. This argues against classical biasing (i.e., protocluster galaxies forming earlier and more efficiently than protofield galaxies) as a way of reconciling cluster $M/L$ with $\Omega = 1$: the only way to much higher cosmic density is to increase the ratio of baryons to dark matter in clusters relative to the cosmic mean, by about a factor of five.

White et al. dispense with the galaxies altogether, and use the baryon to dark matter ratio directly. They use simulations and physical models of cluster collapse to show that composition within the virial radius ought to be representative of the global baryon/dark matter mix for collisionless cold dark matter models. The above estimate for $\Omega_bh^2$ yields $\Omega = 0.12h^{-0.5}$—again implying an open universe, or else a flat universe with an unclustered mass density, such as a cosmological constant.

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3 In some gas-rich, star-poor dwarfs the rotation curve can be measured out to many scale lengths; there are cases (eg, DDO 154) where $M/L$ is more than $50h^3$ (Rubin 1993). Since these are not typical galaxies (the luminosity per baryon is known to be less than usual), it is hazardous to use their $M/L$ as a universal value (their bias is to overestimate $\Omega$).

4 Although they used Coma specifically, similar numbers are obtained in other clusters, using other techniques; for example, Squires et al.1995 derive from weak lensing mass estimators an upper limit of $M_{\text{gas}}/M \leq (0.04 \pm 0.02)h^{-3/2}$ and $M/L_B = (440 \pm 80)h$ for the inner 400kpc of A2218.
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