DEUTERONOMY AND NUMBERS

David N. Schramm and Michael S. Turner

Four light isotopes – D, ³He, ⁴He and ⁷Li – were produced by nuclear reactions a few seconds after the big bang. New measurements of ³He in the ISM by Gloeckler and Geiss (described on page xx of this issue) and of deuterium in high redshift hydrogen clouds by Tytler and his collaborators (described on page xx of this issue) provide further confirmation of big-bang nucleosynthesis and new insight about the density of ordinary matter (baryons).

Helium-4 is produced in the greatest abundance, by mass about 24%. The large primeval abundance of ⁴He, between 22% and 25%, provided the first confirmation of big-bang nucleosynthesis. The other light elements are produced in much smaller amounts, D and ³He around $10^{-5} - 10^{-4}$ relative to hydrogen and ⁷Li around $10^{-10}$ relative to hydrogen, but play important roles in testing the theory.

The big-bang production of ⁴He is relatively insensitive to the density of matter. The yields of the other three light nuclei are much more sensitive to the density and have the potential to not only test the theory, but provide information about the mean density of ordinary matter in the Universe (see Figure).

The great success of primordial nucleosynthesis is that it can account for the primeval abundances of all four light elements (relative to hydrogen) provided the baryon density is between $1.5 \times 10^{-31} \text{g cm}^{-3}$ and $4.5 \times 10^{-31} \text{g cm}^{-3}$. The consistency of the light-element abundances both tests the big-bang cosmological model to within a fraction of a second of the bang and provides the best “measurement” of the density of ordinary matter.
Because big-bang deuterium production decreases rapidly with baryon density and its post big-bang history (or chemical evolution) is simple – stars only destroy D – it is the best baryometer. In the 1970’s the first measurements of the D abundance in the solar system and in the local interstellar medium indicated that matter in the form of baryons could account for at most 15% of the critical density; this conclusion still holds today. Because of possible depletion in stars, the present day deuterium abundance provides a lower limit to the primeval value and thereby an upper limit to the baryon density. (Terrestrial measurements of deuterium are of little cosmological use because of severe isotopic fractionation effects.)

In 1976 Adams proposed a way of measuring the deuterium abundance in very primitive samples of the cosmos where stellar depletion would not be a concern. From such a measurement the baryon density could be inferred to an accuracy of 15% or so. He suggested that the deuterium Ly-α line, which in the rest frame is only 0.33 Å blueward of the usual 1216 Å Ly-α line, might be detected in the wings of Ly-α absorption of high-redshift hydrogen clouds backlit by distant QSOs.

For very distant clouds the UV lines of the Lyman series of hydrogen lines are shifted into the visible spectrum where they can be detected with ground-based instruments. But still, this is no mean feat. Isolated hydrogen clouds of high column density and small velocity dispersion have to be found if the much weaker deuterium feature is to be detected. The very high spectral resolution and signal-to-noise ratio needed demands the best instruments and largest telescopes.

With the advent of the 10 meter Keck Telescope with its high-resolution echelle spectrograph (HIRES) the dream is becoming reality. In the past eighteen months three detections and four tentative detections have been reported. The hydrogen clouds studied are old – redshifts between 2.6 and 4.7 – and pristine – heavy-element abundances ranging between $10^{-2}$ and less than $3 \times 10^{-4}$ of that in the solar system. (Heavy elements are made by stellar processes, not in the big bang.) The values measured for the deuterium abundance fall into
the range anticipated and provide a dramatic confirmation of the big-bang prediction.

The two clouds studied by Tytler and his collaborators have well determined D abundances, \((D/H) = (2.3 \pm 0.3) \times 10^{-5}\) and \((2.5 \pm 0.3) \times 10^{-5}\), and indicate a baryon density of \((4.4 \pm 0.6) \times 10^{-31}\) g cm\(^{-3}\). The cloud studied by Songaila and her collaborators\(^4\) and Carswell and his collaborators\(^5\) has a much higher abundance, \((D/H) = (2 \pm 0.4) \times 10^{-4}\), and indicates a baryon density of \((1.3 \pm 0.3) \times 10^{-31}\) g cm\(^{-3}\). The four tentative detections fall in between.

Any deuterium detection is most conservatively interpreted as an upper limit to the primeval abundance because of the possibility of a low-column-density hydrogen cloud fortuitously located to mimic the deuterium feature (an interloper). Thus, the feature indicating a high value of deuterium might be a hydrogen interloper, with the low value of deuterium reflecting the primeval abundance. If this is the case the baryon density is at the high end of the range anticipated, around 5% of the critical density for a Hubble constant of 70 km s\(^{-1}\) Mpc\(^{-1}\).

However, Rugers and Hogan\(^6\) estimate the chance probability of an interloper at less than 10%, and suggest a more radical hypothesis. They propose that the material in the Tytler clouds has undergone significant stellar processing which has reduced the deuterium abundance by a factor of ten. Because the abundance of heavy elements in the Tytler clouds suggests little stellar processing has occurred, Rugers and Hogan argue the cloud is very inhomogeneous and the heavy elements have been dispersed. This is not implausible since the material giving rise to the absorption lines amounts to only tens of solar masses.

Should the primeval deuterium abundance be high, the inferred baryon density is very low, around 1% for a Hubble constant of 70 km s\(^{-1}\) Mpc\(^{-1}\), making the case for exotic, non-baryonic dark matter ironclad as all estimates for the total matter density exceed 10%, and many by a wide margin. However, a high primeval D abundance requires that more than 90% of the material in the local ISM has been though stars at least once since measurements
made by the Hubble Space Telescope\cite{7} indicate that \((D/H)_{\text{ISM}} = (1.6 \pm 0.1) \times 10^{-5}\). This runs
counter to many models of the chemical evolution of our galaxy and is strongly constrained
by Gloeckler and Geiss’ \(^3\text{He}\) measurement.

Deuterium is first burnt to \(^3\text{He}\), which, according to conventional stellar models, is much
more difficult to destroy, suggesting that a high primeval deuterium abundance should be
reflected in a high \(^3\text{He}\) abundance in the ISM. The measurement by Gloeckler and Geiss of
the \(^3\text{He}\) abundance in the local ISM, \((^{3}\text{He}/H)_{\text{ISM}} = (2.1^{+0.9}_{-0.8}) \times 10^{-5}\), precludes this possibility.
Further, the sum of the D and \(^3\text{He}\) ISM abundances is essentially equal to that inferred for
the solar system 4.5 Gyr ago, \([(D+^{3}\text{He})/H]_{\odot} = (4.2 \pm 1) \times 10^{-5}\), suggesting stars increase
\(^3\text{He}\) by burning D, but do not otherwise significantly deplete or produce it.

Conventional stellar wisdom also predicts that the sum of D + \(^3\text{He}\) should grow signifi-
cantly with time due to \(^3\text{He}\) production by low-mass stars\cite{8}. The measurement by Gloeckler
and Geiss is inconsistent with this prediction. While their measurement has shed some light
on the chemical evolution of \(^3\text{He}\), it has also cast doubt on the conventional wisdom. At this
moment, any argument for or against a particular value of the primeval deuterium abundance
based upon the chemical evolution of \(^3\text{He}\) holds little weight.

There are also pieces missing in the \(^7\text{Li}\) story. Its abundance is measured in the atmo-
spheres of the oldest stars in the halo of the Galaxy, \((^{7}\text{Li}/H) = 1.5 \pm 0.5 \times 10^{-10}\). If this is
the primordial value, it favors a low baryon density (high deuterium). However, some stellar
models indicate that these stars could have reduced their initial \(^7\text{Li}\) abundance by a factor
as large as two, in which case it could be consistent with a high baryon density (low primeval
deuterium).

The Keck Telescope makes it a good bet that within a few years the primeval deuterium
abundance will be determined unambiguously, and with it the value of the baryon density.
An important check may come a few years later from detailed mapping of the anisotropy
of the cosmic background radiation which provides an independent way of determining the
baryon density to similar precision\(^9\). Once the baryon density is known, nuclear physics in the early Universe can be used to teach us about the “chemistry” of \(^3\)He and \(^7\)Li in the interstellar medium.

David N. Schramm and Michael S. Turner are Professors in the Departments of Astronomy & Astrophysics and Physics at The University of Chicago, Chicago, IL 60637-1433, USA.

References

[1] C. J. Copi, D. N. Schramm, and M. S. Turner, *Science* **267**, 192-199 (1995).

[2] R. I. Epstein, J. M. Lattimer, and D. N. Schramm, *Nature* **263**, 198 (1976).

[3] F. T. Adams, *Astron. Astrophys.* **50**, 461-462 (1976).

[4] A. Songaila, L. L. Cowie, C. J. Hogan, and M. Rugers, *Nature* **368**, 599-603 (1994).

[5] R. F. Carswell, M. Rauch, R. J. Weymann, A. J. Cooke, and J. K. Webb, *Mon. Not. R. astr. Soc.* **268**, L1-L4 (1994).

[6] M. Rugers and C. J. Hogan, *Astrophys. J.* **459**, L1 (1996).

[7] J. L. Linsky, A. Diplas, B. E. Wood, A. Brown, T. R. Ayres, and B. D. Savage, *Astrophys. J.* **451**, 335 (1995).

[8] I. Iben and J. W. Truran, *Astrophys. J.* **220**, 980 (1978).

[9] G. Jungman, M. Kamionkowski, A. Kosowsky, and D. Spergel, [astro-ph/9512139](http://arxiv.org/abs/astro-ph/9512139) (1995).
Figure 1: Summary of big-bang production of the light elements. The widths of the curves indicate the 2σ theoretical uncertainties, and the vertical band is the consistency interval where the abundances of all four light elements agree with their measured primeval abundances. The critical density, which depends upon the square of the Hubble constant, is indicated for $H_0 = 70 \text{ km s}^{-1}\text{ Mpc}^{-1}$. The arrows indicate the deuterium abundances measured by Tytler et al. and Songaila et al. The figure is courtesy of C. Copi.