PRIMORDIAL NUCLEI AND THEIR GALACTIC EVOLUTION

Cover figure adapted from Schramm, p. 3:
Big Bang Nucleosynthesis abundance yields versus baryon density ($\Omega_b$) for a homogeneous universe.
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The titles in this series are listed at the end of this volume.
PRIMORDIAL NUCLEI AND THEIR GALACTIC EVOLUTION
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Dedicated to the memory of David N. Schramm (1945–1997)
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FOREWORD

The present volume, the fourth one in the “Space Sciences Series of ISSI” (International Space Science Institute), contains the proceedings of a workshop on “Primordial Nuclei and Their Galactic Evolution”, which was held at ISSI in Bern on 6–10 May 1997. This topic was chosen following some general enquiries with the scientific community concerning its desirability and timeliness. Five convenors, D. Duncan, C. Hogan, J. Linsky, N. Prantzos, and H. Reeves (chair) subsequently set up the workshop, nominated a list of invitees, structured the workshop into a series of introductory talks and into six topical working groups (early Universe – extragalactic objects – low-Z stars – galactic disk and galactic evolution – solar nebula – local interstellar medium), and described the tasks of the working groups in a list of keywords.

It is the main task of ISSI to bring together space scientists, ground-based observers, and theorists from different fields and to give them the opportunity to discuss and compare their results, thus contributing to the achievement of a deeper understanding, adding value to those results through multi-disciplinary research in an atmosphere of international co-operation. In that spirit the convenors selected participants working in fields ranging from Big Bang theory to observers of today’s Solar System, thus spanning the widest possible range both in time and space. The fields were first presented in 18 introductory talks, whereupon the workshop was split into the working groups to which ample time was allocated for individual and joint splinter meetings. In that way, data from at least a dozen space missions (Apollo, ASCA, COBE, Exosat, Galileo, Hipparcos, HST, ISO, ISEE-3, ORFEUS, ROSAT, Ulysses, ...) and from a large number of ground-based telescopes were presented, compared and discussed. Each working group was concluded by a rapporteur presentation in the plenary, summarising the discussions, the achieved progress, the remaining gaps in our understanding, and pointing out directions for future research. The present volume is a collection of the papers resulting from the invited, contributed, and rapporteur presentations, each of which was reviewed by an independent referee. The papers are arranged into six sections, one for each working group, thus closely resembling the structure of the workshop. Finally, the volume is concluded with a workshop summary as an epilogue.

We wish to express our sincere thanks to all those who have made this volume possible. First of all, we should like to thank the authors for writing original articles, for keeping to the various deadlines, and for producing unusually neat camera-ready versions. We also thank the reviewers for their critical and timely reports, which have significantly contributed to the quality of this volume. Finally, it is our pleasure to thank ISSI, in particular its directors J. Geiss and B. Hultqvist, for taking the initiative to host and to support this workshop, the ISSI staff, V. Manno,
G. Nusser Jiang, M. Preen, D. Taylor, and S. Wenger, for the local organization of this workshop, and U. Pfander and X. Schneider for their assistance in the preparation of this volume.

At the time when this volume was going to press, we (as the rest of the scientific community) were saddened by the death of David Schramm. It was a great loss, not only to his family and friends, but also to physics in general and the field of primordial nucleosynthesis in particular.

Indeed, perhaps more than anybody else in the past quarter century, Dave contributed to improving the model of the Hot Early Universe to the status of a theory, bringing together the disciplines of particle physics, nuclear physics and cosmology. His most fundamental contribution to physics is probably the calculation of the number of neutrino families, using arguments from primordial nucleosynthesis. At a time when two families of elementary particles were known and most physicists assumed that many more particle families would be found, Dave and his colleagues boldly predicted in the seventies that only one more family should be expected. The prediction was spectacularly confirmed in the late eighties, by experiments at CERN and in Stanford, revealing the predictive power of the Hot Early Universe theory.

Dave’s work on primordial nucleosynthesis was crucial to the establishment of this “third pillar” of modern Big Bang cosmology (after Hubble’s cosmic expansion and the cosmic microwave background). Furthermore, his calculation of the amount of “ordinary” (baryonic) matter in the universe showed that it accounts for only a small fraction of the total, thus requiring the existence of some form of “exotic” matter. Despite his unshakeable faith on the validity of the Big Bang theory (making him its most prominent defender), Dave always tried to put it on the most firm observational basis, seeking for new observational data. It is in that spirit that he participated in the ISSI conference in May 1997, delivering once more the “message” with his characteristic brilliant and pedagogical style. Dedicating this volume to his memory is then the least tribute we can offer to Dave Schramm, one of the towering figures of modern astrophysics.

February 1998
N. Prantzos, M. Tosi, R. von Steiger
I: EARLY UNIVERSE
BIG BANG NUCLEOSYNTHESIS AND THE DENSITY OF BARYONS IN THE UNIVERSE

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Abstract. Now that extragalactic deuterium observations are being made, Big Bang Nucleosynthesis (BBN) is on the verge of undergoing a transformation. Previously, the emphasis was on demonstrating the concordance of the Big Bang Nucleosynthesis model with the abundances of the light isotopes extrapolated back to their primordial values using stellar and Galactic evolution theories. Once the primordial deuterium abundance is converged upon, the nature of the field will shift to using the much more precise primordial D/H to constrain the more flexible stellar and Galactic evolution models (although the question of potential systematic error in $^4$He abundance determinations remains open). The remarkable success of the theory to date in establishing the concordance has led to the very robust conclusion of BBN regarding the baryon density. The BBN constraints on the cosmological baryon density are reviewed and demonstrate that the bulk of the baryons are dark and also that the bulk of the matter in the universe is non-baryonic. Comparison of baryonic density arguments from Lyman-$\alpha$ clouds, x-ray gas in clusters, and the microwave anisotropy are made and shown to be consistent with the BBN value.

Key words: Cosmology, Nucleosynthesis, Light Elements

Abbreviations: HST – Hubble Space Telescope; ISM – Interstellar Medium; LEP – Large Electron Positron Collider; SLC – Stanford Linear Collider; ROSAT – German X-ray satellite; ASCA – Japanese X-ray satellite; ESA – European Space Agency; CDM – cold dark matter

1. Introduction

The study of Big Bang Nucleosynthesis and the light element abundances is undergoing a major transformation. The bottom line remains: primordial nucleosynthesis has joined the Hubble expansion and the microwave background radiation as one of the three pillars of Big Bang cosmology. Of the three, Big Bang Nucleosynthesis (BBN) probes the universe to far earlier times ($\sim 1$ sec) than the other two and led to the interplay of cosmology with nuclear and particle physics. Furthermore, since the Hubble expansion is also part of alternative cosmologies such as the steady state, it is BBN and the microwave background that really drive us to the conclusion that the early universe was hot and dense. The new extragalactic deuterium observations not only cement this picture and give added convergence on a value of the baryon density, $\Omega_b$, they also enable BBN to become a constraint on stellar and Galactic evolution scenarios. It is this latter point that is the core of the transformation. Furthermore, new alternative methods of estimating the cosmic baryon density are now coming into use and are independently confirming the BBN prediction.
The current review will draw heavily on the recent review by Schramm (1997) in *Proceedings of the National Academy of Sciences*.

### 2. Overview

Although the extragalactic D/H observations have naturally attracted the most attention, it should not be forgotten that there are also recent heroic observations of $^6$Li, Be and B, as well as $^3$He and new $^4$He determinations. Let us now briefly review the history, with special emphasis on the remarkable agreement of the observed light element abundances with the calculations. This agreement works only if the baryon density is well below the cosmological critical value. We will also note how a convergence on extragalactic D/H will enable powerful new constraints on stellar and Galactic evolution.

It should be noted that there is a symbiotic connection between BBN and the 3K background dating back to Gamow and his associates, Alpher and Herman. The initial BBN calculations of Gamow's group (Alpher *et al.*, 1948) assumed pure neutrons as an initial condition and thus were not particularly accurate, but their inaccuracies had little effect on the group’s predictions for a background radiation. Once Hayashi (1950) recognized the role of neutron-proton equilibration, the framework for BBN calculations themselves has not varied significantly. The work of Alpher, Follin and Herman (1953) and Tayler and Hoyle (1964), preceeding the discovery of the 3K background, and of Peebles (1966) and Wagoner, Fowler and Hoyle (1967), immediately following the discovery, and the more recent work of our group of collaborators (Copi *et al.*, 1997; Copi *et al.*, 1994; Walker *et al.*, 1991; Olive *et al.*, 1990; Schramm and Wagoner, 1977; Olive *et al.*, 1981; Yang *et al.*, 1984; Kawano *et al.*, 1988) all do essentially the same basic calculation, the results of which are shown in Figure 1.

As far as the calculation itself goes, solving the reaction network is relatively simple by the standards of explosive nucleosynthesis calculations in supernovae, with the changes over the last 25 years being mainly in terms of more recent nuclear reaction rates as input, not as any great calculational insight, although the current Kawano code (Kawano *et al.*, 1988) is somewhat streamlined relative to the earlier Wagoner code. In fact, the earlier Wagoner code (Wagoner *et al.*, 1967) is, in some sense, a special adaptation of the larger nuclear network calculation developed by Truran (1965; Truran *et al.*, 1966) for work on explosive nucleosynthesis in supernovae. With the exception of Li yields and non-yields of Be and B (Steigman *et al.*, 1993), the reaction rate changes over the past 25 years have not had any major effect [see Yang *et al.* (1984) and Krauss and his collaborators (Krauss and Romanelli, 1990; Kernan and Krauss, 1994), or Copi, Schramm, and Turner (1994) for a discussion of uncertainties]. The one key improved input is a better neutron lifetime determination (Mampe *et al.*, 1989; Mampe *et al.*, 1993). There has been much improvement in the $t(\alpha, \gamma)^7$Li reaction rate, but as the width of the curves
in Figure 1 shows, the $^7\text{Li}$ yields are still the poorest determined, both because of this reaction and even more because of the poorly measured $^3\text{He}(\alpha, \gamma)^7\text{Be}$.

With the exception of the effects of elementary particle assumptions, to which we will return, the real excitement for BBN over the last 25 years has not really been in redoing the basic calculation. Instead, the true action is focused on understanding the evolution of the light element abundances and using that information to make powerful conclusions. In the 1960's, the main focus was on $^4\text{He}$ which is very insensitive to the baryon density. The agreement between BBN predictions and observations helped support the basic Big Bang model but gave no significant information, at that time, with regard to density. In fact, in the mid-1960's, the other light isotopes (which are, in principle, capable of giving density information) were
generally assumed to have been made during the T-Tauri phase of stellar evolution (Fowler et al., 1962), and so, were not then taken to have cosmological significance. It was during the 1970's that BBN fully developed as a tool for probing the universe. This possibility was in part stimulated by Ryter et al. (1970) who showed that the T-Tauri mechanism for light element synthesis failed. Furthermore, D abundance determinations improved significantly with solar wind measurements (Geiss and Reeves, 1971; Black, 1971) and the interstellar work from the Copernicus satellite (Rogerson and York, 1973). (Recent HST observations reported by Linsky et al. (1993) and Linsky (1998) have compressed the local ISM D error bars considerably.) Reeves, Audouze, Fowler and Schramm (1973) argued for cosmological D and were able to place a constraint on the baryon density excluding a universe closed with baryons. Subsequently, the D arguments were cemented when Epstein, Lattimer and Schramm (1976) proved that no realistic astrophysical process other than the Big Bang could produce significant D. This baryon density was compared with dynamical determinations of density by Gott, Gunn, Schramm and Tinsley (1974). See Figure 2 for an updated $H_0 - \Omega$ diagram.

In the late 1970's, it appeared that a complementary argument to D could be developed using $^3$He. In particular, it was argued (Rood et al., 1976) that, unlike D, $^3$He was made in stars; thus, its abundance would increase with time. Unfortunately, recent data on $^3$He in the interstellar medium (Gloeckler and Geiss, 1996) has shown that $^3$He has been constant for the last 5 Gyr. Thus, low mass stars are not making a significant addition, contrary to these previous theoretical ideas. Furthermore, Rood, Bania and Wilson (1992) have shown that interstellar $^3$He is quite variable in the Galaxy, contrary to expectations for a nucleus produced mainly by low mass stars. However, the work on planetary nebulae shows that at least some low mass stars do produce $^3$He. Nonetheless, the current observational situation clearly shows that arguments based on theoretical ideas about $^3$He evolution should be avoided [c.f. Hata et al. (1995), where their "crisis" is really about $^3$He problems (and excessively small assumed uncertainties in $^4$He), not BBN]. Since $^3$He now seems not to have a well understood history, simple $^3$He or $^3$He+D inventory arguments are misleading at best. However, one is not free to go to arbitrary low baryon densities and high primordial D and $^3$He, since processing of D and $^3$He in massive stars also produces metals which are constrained (Copi et al., 1995; Scully et al., 1996) by the total metal content observed in the hot intra-cluster gas, if not the Galaxy. In the near future, this problem with $^3$He evolution will be severely constrained by the extragalactic D/H. In particular, the Tytler and Burles D/H = $3.2 \pm 0.6 \times 10^{-5}$ (discussed at the 1997 Trento Workshop) is only slightly higher than the pre-solar D/H = $2.1 \pm 0.5 \times 10^{-5}$ (Geiss and Gloeckler, 1998) and less than a factor of 2 above the current interstellar D/H = $1.5 \pm 0.1 \times 10^{-5}$ (Linsky, 1998). This tells us that the production of the current metal content of the Galaxy did not destroy much D. This implies either a very different initial mass function in the early history of the Galaxy to make the metals, or much primordial infall throughout the history of the Galaxy to replenish the deuterium abundance.
It was interesting that the abundances of the other light elements led to the requirement that $^7\text{Li}$ be near its minimum of $^7\text{Li}/H \sim 10^{-10}$, which was verified by the Pop II Li measurements of Spite and Spite (1982; Rebolo et al., 1988; Hobbs and Pilachowski, 1988), hence yielding the situation emphasized by Yang et al. (1984) that the light element abundances are consistent over nine orders of magnitude with BBN, but only if the cosmological baryon density, $\Omega_b$, is constrained to be around 6% of the critical value (for $H_0 \approx 50$ km/sec/Mpc). The Li plateau argument was further strengthened with the observation of $^6\text{Li}$ in a Pop II star by Smith, Lambert and Nissen (1993). Since $^6\text{Li}$ is much more fragile than $^7\text{Li}$, and yet it survived, no significant nuclear depletion of $^7\text{Li}$ is possible (Steigman et al., 1993; Olive and Schramm, 1992; Lemoine et al., 1997). This observation of $^6\text{Li}$ was verified by Hobbs and Thorburn (1994). Lithium depletion mechanisms are also severely constrained by the recent work of Spite et al. (1996) showing that the lithium plateau is also found in Pop II tidally locked binaries. Thus, meridional
mixing is not causing significant lithium depletion. Recently Nollett et al. (1997) have discussed how \(^6\text{Li}\) itself might eventually become another direct probe of BBN depending on the eventual low energy measurement of the \(D(\alpha, \gamma)^6\text{Li}\) cross section and on spectroscopy improvements for extreme metal-poor dwarfs. With the new extragalactic \(\text{D/H}\), one should be able to turn the \(^7\text{Li}\) argument around and argue how much depletion and/or what model atmosphere is necessary. It is again clear from this argument that large amounts of depletion did not occur, contrary to the earlier models of Delyannis (1995).

Another development back in the 70’s for BBN was the explicit calculation of Steigman, Schramm and Gunn (1977) showing that the number of neutrino generations, \(N_\nu\), had to be small to avoid overproduction of \(^4\text{He}\). [Earlier work (Tayler and Hoyle, 1964; Schwartzman, 1969; Peebles, 1971) had commented about a dependence on the energy density of exotic particles but had not done an explicit calculation probing \(N_\nu\).] To put this in perspective, one should remember that the mid-1970’s also saw the discovery of charm, bottom and tau, so that it almost seemed as if each new detector produced new fundamental particle discoveries, and yet, cosmology was arguing against this “conventional” wisdom. Over the years, the limit on \(N_\nu\) improved with \(^4\text{He}\) abundance measurements, neutron lifetime measurements, and with limits on the lower bound to the baryon density, hovering at \(N_\nu \lesssim 4\) for most of the 1980’s and dropping to slightly lower than 4 just before LEP and SLC turned on (Walker et al., 1991; Olive et al., 1990; Schramm and Kawano, 1989; Pagels, 1991). This was verified by the LEP Collaboration results (1992) (see also the CERN preprint CERN-PPE/96-183, 1996) where now the overall average is \(N_\nu = 2.987 \pm 0.02\). A recent examination of the cosmological neutrino limit by Copi et al. (1997) in the light of the recent \(^3\text{He}\) and \(\text{D/H}\) work shows that the BBN limit remains between 3 and 4 for all reasonable assumption options. It should be noted that this limit remains robust despite the uncertainties on \(^4\text{He}\) systematics, since those uncertainties are still relatively small compared to a \(\Delta N_\nu\) of unity, although they are not small compared to significant shifts in \(^4\text{He}\) implications for \(\Omega_b\).

The recent apparent convergence of the extra-galactic \(\text{D/H}\) measurements towards the lower values (Tytler, 1998; Hogan, 1997) \(\text{D/H} \sim 3 \times 10^{-5}\) is beginning to collapse the \(\Omega_b\) band in Figure 1 to a relatively narrow strip on the high \(\Omega_b\) side (see arrows). However, such a full collapse at present is probably a bit premature. In any case, it is clear that deuteronomy (the study of deuterium in the cosmos) is a success since: 1) deuterium is clearly cosmological as it is seen in low metalicity and high redshift Lyman-\(\alpha\) clouds; 2) the primordial \(\text{D/H}\) is higher than the present ISM \(\text{D/H}\), as predicted by theory; and 3) the range of values for primordial \(\text{D/H}\), regardless of whether or not the high or low ones win out, is consistent with the range of expectations based on the other light nuclei.

One potential problem that the “low \(\text{D/H}, \text{high } \Omega_b\)” solution raises is the fact that the central primordial \(^4\text{He}\) mass fraction is \(\sim 0.23\), rather than \(\sim 0.245\), which the Tytler and Burles (Tytler et al., 1996; Tytler, 1998) \(\text{D/H}\) value would prefer for
concordance. However, as Copi et al. (1997) emphasize, systematic uncertainties in $Y_p$ cannot rule out such an excursion. But clearly we have to look carefully at $^4$He. The recent work of Izotov's group (Thuan et al., 1996) on $Y_p \sim 0.24$ shows how uncertain the present situation is, but the resolution remains to be found. How high $Y_p$ can be and still be consistent with the He observations in extragalactic H-II regions is still quite debatable, although most agree that $Y_p$ up to 0.25 is not impossible. Schram and Turner (1998) show that a Bayesian analysis of the plausible upper limit on $Y_p$ centers on 0.25.

The power of homogeneous BBN comes from the fact that essentially all of the physics input is well determined in the terrestrial laboratory. The appropriate temperature regimes, 0.1 to 1 MeV, are well explored in nuclear physics laboratories. Thus, what nuclei do under such conditions is not a matter of guesswork, but is precisely known. In fact, it is known for these temperatures far better than it is for the centers of stars like our Sun. The center of the Sun is only a little over 1 keV, thus, below the energy where nuclear reaction rates yield significant results in laboratory experiments, and only the long times and higher densities available in stars enable anything to take place.

3. Density of Baryons

The bottom line that emerges from the above discussion is that (Copi et al., 1997)

$$0.01 \lesssim \Omega_b h_0^2 \lesssim 0.025$$

where $h_0 \equiv H_0(km/sec/Mpc)/100$. If the Tytler arguments on D/H do indeed hold up, then this will compress towards the high side, say $\Omega_b h^2 \sim 0.02 \pm 0.005$. Let us now compare with other ways of estimating $\Omega_b$.

Attempts to circumvent the conclusion of homogeneous BBN by invoking a first-order quark-hadron phase transition (Applegate et al., 1988; Alcock et al., 1987) have merely illustrated the robustness of the conclusions. Figure 3 illustrates this fact, showing that for an optimized first-order quark-hadron phase transition, the abundances are only fit for the same range in $\Omega_b h^2$ as in the homogeneous case. Only if the lithium constraint is completely ignored can higher $\Omega_b h^2$ values work, and even then, only a factor of 2 is possible.

3.1. LYMAN-α CLOUDS

Recent work by Bi and Davidsen (1997), by Quashnock and Vanden Berk (1997), and by Weinberg et al. (1997) also argues that the density of gas in the form of Lyman-α clouds at high redshift is consistent with the high end of the Big Bang Nucleosynthesis range on $\Omega_b$. This would appear to resolve the long time problem of where are the "dark baryons." It is well known that $\Omega_{\text{visible}} \lesssim 0.01$, which, when compared to $\Omega_{\text{BBN}}$, implies that the bulk of the baryons are not associated
with stellar material. At least at high redshift this unseen material appears to have been found in these Lyman-α clouds. In conjunction with the Lyman-α clouds, it should also be noted that singly ionized helium is seen in the intergalactic gas, thus supporting the BBN fact that helium is primordial, and also supporting the point that significant numbers of baryons were between galaxies at high redshift (Jakobsen et al., 1994; Bi and Davidsen, 1997).

3.2. HOT GAS IN CLUSTERS

Hot gas has been found in clusters of galaxies by ROSAT and ASCA. The temperature of the gas can be used to estimate the gravitational potential of the clusters if it is assumed that the gas is virialized and purely supported by thermal pressure. Similarly, the intensity of the emission can be used to estimate the density of the gas. White et al. (1993) have shown that the typical values for x-ray clusters yield a hot gas to total mass ratio $M_{\text{HOT}}/M_{\text{TOT}}$ of about 0.2.

Cluster masses can be estimated either from the temperature of the hot gas or from dynamics or from gravitational lensing. All yield the cluster implied density, $\Omega_{\text{CLUSTER}}$, of $\sim 0.25 \pm 0.10$. Thus, the implied baryon density from x-ray gas in clusters, $\Omega_{\text{b,CLUSTER}} \approx \frac{M_{\text{HOT}}}{M_{\text{TOT}}} \times \Omega_{\text{CLUSTER}} \sim 0.05$, in good agreement with the BBN value for $H_0 = 50$ km/s/Mpc and for the Tytler D/H.