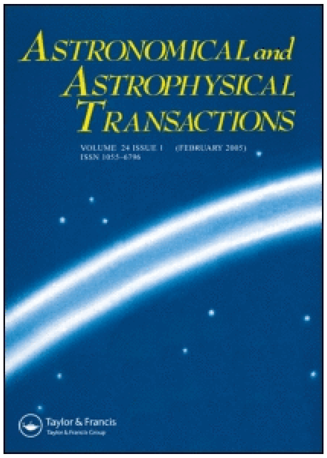

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PRIMORDIAL NUCLEOSYNTHESIS

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I summarize recent developments in the study of primordial nucleosynthesis. The most dramatic development is the availability of direct high-redshift measurements of the primordial deuterium abundance. Theoretical developments include the more accurate treatment of higher-order effects in the prediction of the ^{4}He abundance, and a better understanding of the errors in the theoretical predictions of the element abundances. The future will surely see increasing reliance on deuterium to determine the baryon density, with the other elements used primarily as a check on the accuracy of the theory.

KEY WORDS Primordial nucleosynthesis, deuterium abundance, barion density

1 INTRODUCTION: THE STANDARD MODEL OF PRIMORDIAL NUCLEOSYNTHESIS

It is, of course, appropriate to discuss primordial nucleosynthesis at a conference in honour of George Gamow, since Gamow was one of the earliest pioneers in this field. Let me first review the standard model for primordial nucleosynthesis, which achieved its present form in the seminal work of Wagoner, Fowler, and Hoyle (1967). At temperatures $T > 10^{10}$ K, the weak reactions which interconvert neutrons and protons,

$$p + e^- \leftrightarrow n + \nu_e, \tag{1}$$

$$p + \bar{\nu}_e \leftrightarrow n + e^+, \tag{2}$$

$$n \leftrightarrow p + e^- + \bar{\nu}_e \tag{3}$$

operate fast enough to maintain the neutrons and protons in their thermal equilibrium abundances. When the temperature drops to $T \sim 10^{10}$ K, these reactions 'freeze out'. Roughly speaking, this means that the reaction rates for these processes, multiplied by the age of the universe, drop below one, so that the probability for a single proton to be converted to a neutron (or vice versa) drops below unity, and the relative abundances of protons and neutrons are frozen at a ratio of $n/p \sim 1/6$. The exception to this is free neutron decay, which continues to operate at temperatures below 10^{10} K and reduces the n/p ratio below its freeze-out value. Then, at $T \sim 10^9$ K, the nuclear reaction rates become large relative to the corresponding photodestruction rates, allowing rapid buildup into heavier elements via

$$\begin{aligned} n + p &\rightarrow \mathrm{D}, \\ \mathrm{D} + p &\rightarrow {}^3\mathrm{He}, \\ \mathrm{D} + n &\rightarrow {}^3\mathrm{He}, \\ {}^3\mathrm{He} + \mathrm{D} &\rightarrow {}^4\mathrm{He} + p, \\ {}^3\mathrm{H} + \mathrm{D} &\rightarrow {}^4\mathrm{He} + n, \end{aligned} \tag{4}$$

and reactions which build on ^{4}He to produce heavier elements, most importantly ^{7}Li. Essentially all of the free neutrons end up in ^{4}He, with the leftover protons giving hydrogen, but D, ^{7}Li and ^{3}He are also produced in trace amounts.

The abundances predicted by the standard primordial nucleosynthesis model are very sensitive to the baryon density ρ_B during nucleosynthesis. Because ρ_B is a function of the scale factor, it is convenient to parametrize it in terms of the baryon-to-photon ratio $\eta \equiv n_\mathrm{B}/n_\gamma$, which is a constant in the absence of significant photon production after nucleosynthesis. In terms of Ω_B the baryonic contribution to Ω) we have the relation:

$$\Omega_\mathrm{B} h^2 = 3.6 \times 10^7 \eta. \tag{5}$$

The nuclear reaction rates in equations (4) are all increasing functions of η. For the case of ^{4}He, an increase in these reaction rates (from an increase in η) causes the buildup into heavier elements to occur earlier, allowing less time for free neutron decay and therefore giving more neutrons to produce more ^{4}He. Increasing the reaction rates allows more deuterium to be burned into heavier elements, giving a deuterium abundance which is a decreasing function of η. The behaviour of ^{7}Li with η is more complicated.

Because these element abundances are sensitive to the value of η, primordial nucleosynthesis provides very stringent cosmological bounds on the baryon density. The problem is that the element abundances we see today are not identical to the primordial abundances. Therefore, it is necessary first to use the presently observed element abundances to infer the primordial abundances, then to combine these primordial abundances with the theoretical predictions of primordial nucleosynthesis to determine η and Ω_B.

The last few years have seen some very interesting new results in this field, primarily because of improved observational constraints on the primordial element abundances. However, I will discuss both observational and theoretical results in this talk. In the next section, I will examine the progress that has been made in sharpening the limits on the primordial deuterium, helium-4, and lithium abundances. In Section 3, I will examine recent new theoretical results, including both high precision corrections to the standard model of primordial nucleosynthesis, and non-standard theoretical models. Finally, in Section 4, I will discuss the agreement between theory and observation, and give the corresponding results for the baryon abundance. I will also examine the direction in which this field is moving in the near future.

2 OBSERVATIONAL DEVELOPMENTS

To illustrate the progress which has been made in constraining the primordial element abundances over the past decade, consider the limits presented in two review papers, by Walker *et al.* (1991) and by Olive, Steigman, and Walker (1999). The 1991 limits are (Walker *et al.*, 1991):

$$\begin{aligned} \mathrm{D/H} &> 1.8 \times 10^{-5}, \\ (\mathrm{D} + {}^3\mathrm{He})/\mathrm{H} &< 1.0 \times 10^{-4}, \\ \mathrm{Y}_P &= 0.22\text{–}0.24, \\ {}^7\mathrm{Li/H} &< 1.4 \times 10^{-10}, \end{aligned} \tag{6}$$

while the limits from 1999 are (Olive *et al.*, 1999):

$$\mathrm{D/H} = 2.9\text{–}4.0 \times 10^{-5},$$

or

$$\begin{aligned} \mathrm{D/H} &= 1\text{–}3 \times 10^{-4}, \\ \mathrm{Y}_P &= 0.228\text{–}0.248, \\ {}^7\mathrm{Li/H} &= 1.2\text{–}2.0 \times 10^{-10}. \end{aligned} \tag{7}$$

The most striking difference between the estimated element abundances occurs in the limits for deuterium. The earlier paper contains only a lower bound for deuterium, while giving an upper bound on the sum of the deuterium and helium-3 abundances. In contrast, the more recent work gives extremely sharp limits on the primordial deuterium.

Until recently, our knowledge of deuterium was limited by our ignorance of the details of stellar processing between the epoch of nucleosynthesis and today. However, it is well-established that stars destroy deuterium, and there are no obvious astrophysical sites for producing deuterium outside of the Big Bang. Hence, the observed deuterium abundance in the interstellar medium provides a lower bound on the primordial abundance, giving an upper bound on η. The problem with this approach is that it produces no upper limit on the primordial deuterium. However, the deuterium destroyed in stars is processed into helium-3, some of which survives to the present day, so various arguments were attempted to put an upper limit on the sum of the deuterium and helium-3 abundances (see, for example, Walker *et al.*, 1991).

All of these arguments have been superseded in the past few years as, for the first time, we have direct observations of the primordial deuterium abundance. These observations involve absorption line studies of high-redshift, low-metallicity Lyman-α clouds, primarily by Tytler and collaborators (Tytler *et al.*, 1996; Burles and Tytler, 1998a, b). These clouds are 'illuminated' by background QSO's, and the deuterium can be distinguished from the hydrogen by the isotope shift. The material in these clouds is presumably primordial, but there are still some complications involved in these measurements. Hydrogen with the correct peculiar velocity can resemble deuterium, if the peculiar redshift is equal to the deuterium isotope shift. Furthermore, as emphasized by Levshakov and collaborators, the velocity structure of the clouds can have an important effect on the inferred deuterium abundance (Levshakov *et al.*, 1998, 1999, sub.). Despite these caveats, these measurements of the primordial deuterium abundance at high redshift are surely the most important development in primordial nucleosynthesis in the past decade.

The most recent results of Burles and Tytler (1998a, b) give a deuterium abundance of $D/H \sim 3\text{–}4 \times 10^{-5}$, while studies which take into account the velocity structure (Levshakov *et al.*, 1998, 1999, sub.) give a somewhat larger upper bound: $D/H \sim 3\text{–}5 \times 10^{-5}$.

The one discrepancy from these estimates is a much higher deuterium abundance ($D/H \sim 2 \times 10^{-4}$) derived by Webb *et al.* (1997) for a lower-redshift system. This result is inconsistent with all of the other observations, and so probably does not represent the true primordial abundance.

Estimates of the primordial helium-4 abundance have also been sharpened, although not nearly as dramatically. These measurements are made in low-metallicity H II regions. Until fairly recently, the standard technique for estimating the primordial helium-4 abundance was to plot the helium abundance versus the abundance of some other element, such as oxygen or nitrogen, that is produced only after the Big Bang. A linear extrapolation back to a zero abundance of nitrogen or oxygen was then used to give an estimate of Y_P. The problems with this approach are obvious, beginning with the *a priori* nature of the hypothesis that the relation between helium-4 and nitrogen or oxygen is linear. As more regions of very low metallicity have been added to the data set, the standard approach has shifted to simply averaging the values of helium-4 in the lowest metallicity regions. Recent analyses using this approach yield $Y_P = 0.234 \pm 0.003$ (Olive and Steigman, 1995) and $Y_P = 0.244 \pm 0.002$ (Izotov and Thuan, 1998). Obviously, these two values differ by much more than their estimated statistical errors, indicating that systematic errors dominate these results.

3 THEORETICAL DEVELOPMENTS

Theoretical work in primordial nucleosynthesis has proceeded down two very different tracks: increasing the accuracy and understanding the uncertainties in the theoretical predictions of the standard model, and exploring non-standard models for primordial element production.

Following the initial work of Wagoner *et al.* (1967), a number of authors have attempted to refine the theoretical calculations to obtain more accurate element abundances (see, for example, Discus *et al.*, 1982; Seckel, 1993; Lopez *et al.*, 1997; Lopez and Turner, 1999). The primary refinements are corrections to the weak rates, which affect the freeze-out n/p ratio, and thermodynamic corrections, which affect the overall expansion rate of the universe. The former category includes Coulomb corrections, finite temperature effects, and finite mass corrections. The latter category includes QED effects on the plasma equation of state, and the effect of treating the neutrino decoupling exactly. These are all very small effects and are important only for the predicted abundance of ^{4}He. Lopez and Turner (1999) have recently performed an exhaustive calculation of all of these effects; they find that the overall correction to the predicted helium-4 abundance is $\Delta Y \sim +0.005$.

In addition to improving the accuracy of the theoretical predictions, a number of authors have devoted a great deal of work to understanding the theoretical uncertainties in the predicted element abundances (Smith *et al.*, 1993; Hata *et al.*, 1996; Burles *et al.*, 1999). The two major sources of uncertainty are the uncertainty in the neutron lifetime, τ_n, which is used to calibrate all of the $n \leftrightarrow p$ weak rates, and the uncertainties in all of the nuclear reaction cross-sections. The uncertainty in τ_n is the primary source of uncertainty in the predicted ^{4}He abundance, but it has almost no effect on the other element abundances. The uncertainties in the predicted D and ^{7}Li abundances are determined by the uncertainties in the nuclear cross-sections.

In addition to these incremental improvements to the standard theoretical model, theorists have long proposed many non-standard models for primordial nucleosynthesis (see Malaney and Mathews (1993) for a recent review and references). Variations on the standard model include unstable particles or particles which annihilate at late times, inhomogeneous or anisotropic models, neutrino degeneracy, neutrino oscillations, time variation of the fundamental constants, and many others. Although I am sympathetic to these ideas, having worked on many of them myself, I must admit that there is at present no compelling evidence to support any of them.

One set of ideas has been put forth recently to explain the apparent discrepancy between the deuterium abundances observed in different Lyman-α clouds. Cardall and Fuller (1996) suggested that these results could be evidence for large-scale density inhomogeneities, while Dolgov and Pagel (1999) noted that inhomogeneous neutrino degeneracy on very large scales could produce such varying deuterium abundances. Of course, these ideas are irrelevant if the remaining high deuterium observation is shown not to represent the primordial abundance (although the ideas of Dolgov and Pagel (1999) were extended to include the possibility of inhomogeneous neutrino degeneracy producing homogeneous final element abundances in Whitmire and Scherrer).

4 CONCLUSIONS AND THE FUTURE

The fundamental question in the study of primordial nucleosynthesis is whether or not the theory 'works'. Does it give predictions for deuterium, helium-4, and lithium which are consistent with the observations? If we take a very conservative range for deuterium, D/H = 3–5 $\times 10^{-5}$, we find that $\eta = 4\text{–}6 \times 10^{-10}$ (the element abundances corresponding to a particular η value were generated here using the website www.astro.washington.edu/research/bbn/). This corresponds to $\Omega_B h^2 =$ 0.014–0.022, giving $\Omega_B = 0.02\text{–}0.09$ (for $h = 0.5\text{–}0.8$) or $\Omega_B = 0.03\text{–}0.05$ (for $h =$ 0.65). The other element abundances produced with this range of η values are $Y_P = 0.244\text{-}0.247$ and ^{7}Li/H = 1.8–3.6 $\times 10^{-10}$. These abundances are in marginal agreement with the observational limits.

What does the future hold for primordial nucleosynthesis? One obvious trend is an increasing reliance on deuterium observations as the primary constraint on η. Before the advent of the high-redshift observations, theorists tended to treat deuterium, helium-3, helium-4, and lithium-7 on an equal footing, trying to find the values of η which best fit all of these elements. But the high-redshift deuterium observations provide the best estimate of the primordial abundance of any element, and the deuterium abundance is extraordinarily sensitive to η. So we can expect that these observations will be used to determine η, with the resulting value used to predict the ^{4}He and ^{7}Li abundances. The agreement or disagreement of these abundances with the observations will then be seen as a test of the overall theory. Interest in ^{3}He has waned, since it was primarily used as a constraint on the primordial deuterium abundance, as discussed in Section 2.

With better observations and a better understanding of the errors in the predictions of the theoretical abundances, we can expect either better concordance between theory and observations, with increasingly narrower limits on $\Omega_B h^2$, or (much less likely) eventual discordance, requiring a resort to some sort of nonstandard variation. Finally, the high-precision CMB measurements of the coming decade will provide an independent estimate of $\Omega_B h^2$, which can be compared with the predictions of primordial nucleosynthesis.

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