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BARYONIC DARK MATTER AND BIG BANG NUCLEOSYNTHESIS

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ABSTRACT

The recently observed deuterium abundance in low-metallicity high-redshift hydrogen clouds, about 10 times larger than that observed in the local interstellar medium, is in excellent agreement with that predicted by the standard big bang nucleosynthesis theory and by the observed abundances of ^{4}He and ^{7}Li extrapolated to their primordial values if the cosmic baryon-to-photon ratio is $\eta = (1.60 \pm 0.1) \times 10^{-10}$. It implies a mean cosmic baryon density, in critical mass units, of $\Omega_b \approx 0.0058 \pm 0.0007 h^{-2}$, which is consistent with the observed mean cosmic density of matter visible in radio, IR, V, UV, or X-ray wavelengths, if $h \approx 0.8$. It does not provide reliable evidence that most of the baryons in the universe are dark. Moreover, if $\Omega \gtrsim 0.10$, as implied by the dynamics of clusters of galaxies, it indicates that most of the matter in the universe is non-baryonic dark matter.

Subject headings: dark matter — early universe — nuclear reactions, nucleosynthesis, abundances

1. INTRODUCTION

The agreement between the predictions of the standard big bang nucleosynthesis (SBBN) theory and the observed abundances of H, D, ^{3}He, ^{4}He, and ^{7}Li extrapolated to their primordial values, which span about 10 orders of magnitude, is one of the most convincing pieces of supportive evidence for the standard hot big bang model of the early universe. The predictions of SBBN theory (Peebles 1966; Wagoner, Fowler, & Hoyle 1967; Wagoner 1973; Yang et al. 1984) depend on low-energy nuclear cross sections and on three additional parameters, the number of flavors of light neutrinos, N_ν, the neutron lifetime, τ_n, and the ratio of baryons to photons in the universe, $\eta \equiv n_b/n_\gamma$. The relevant nuclear cross sections are now known from laboratory measurements (e.g., Caughlan & Fowler 1988 and references therein). Measurements at the Large Electron Positron Collider (LEP) at CERN gave $N_\nu = 3.04 \pm 0.04$ (e.g., Mana & Martinez 1993). Measurements of τ_n in neutron bottles and Penning traps, coupled with previous measurements, yielded the weighted average (see Particle Data Group 1994) $\tau_n = 887 \pm 2.0$ s. Finally, measurements of the cosmic microwave background radiation by *COBE* (Mather et al. 1994) gave a blackbody temperature $T = 2.726 \pm 0.017$ K, which yields $n_\gamma = 20.28T^3 \approx 411 \pm 8$ cm^{-3}. Hence, SBBN theory predicts quite accurately the primordial abundances of the light elements as a function of a single unknown parameter, n_b, the mean baryon number density in the universe. Thus, the primordial abundances of the light elements, as inferred from observations, can be used to test SBBN theory and determine this number. Indeed, it has been claimed repeatedly that the predictions of SBBN theory agree with observations if $\eta_{10} \equiv \eta \times 10^{10} \approx 4$, which implies that most of the nucleons in the universe are dark (e.g., Kolb & Turner 1990; Walker et al. 1991; Smith, Kawano, & Malaney 1993 and references therein). Moreover, based on these analyses, a variety of limits on the physics beyond the standard particle physics model (new interactions; new weakly interacting particles; additional neutrino flavors; masses, mixings, magnetic moments, decay modes, and lifetimes of neutrinos) were derived by various authors.

However, the claimed concordance between SBBN theory and the observed abundances of the light elements extrapolated to their primordial values had a rather poor confidence level, was demonstrated for a primordial abundance of ^{4}He that deviated significantly from its best value inferred from observations and relies heavily on the highly uncertain extrapolated values for the primordial abundances of D + ^{3}He. Hence, SBBN could provide neither reliable evidence that most of the baryons in the universe are dark nor reliable limits on the physics beyond the standard particle physics model (Dar, Goldberg, & Rudzsky 1992). In fact, Dar et al. (1992) argued that the theoretical upper bound on primordial D + ^{3}He that was estimated by Walker et al. (1991) from a galactic evolution model is highly uncertain and the best values of the primordial abundances of ^{4}He and ^{7}Li as inferred from observations indicate that $\eta_{10} \approx 1.60 \pm 0.10$. This value yields a mean baryon density in the present universe which is consistent with the mean density of matter observed in the V, IR, UV, X-ray, and radio bands. It also predicts a primordial abundance (by number) of D, $[\mathrm{D}]_p/[\mathrm{H}]_p \approx (2.10 \pm 0.20) \times 10^{-4}$, that is larger by about an order of magnitude than that observed in the Galactic interstellar medium (Linsky et al. 1993).

During the past 3 years new observations and refined analyses have greatly improved the estimated values of the primordial abundances of ^{4}He (Pagel et al. 1992; Mathews et al. 1993; Skillman & Kennicutt 1993; Izotov, Thuan, & Lipovetsky, 1994), ^{7}Li (Thorburn 1994), and, in particular, of D (Songaila et al. 1994; Carswell et al. 1994). In this paper we show that these new values for the primordial abundances of D, ^{4}He, and ^{7}Li are in excellent agreement with those predicted by SBBN theory if $\eta_{10} \approx 1.60 \pm 0.10$.

2. THE SBBN-PREDICTED ABUNDANCES

The primordial abundances of ^{4}He, D, ^{3}He, and ^{7}Li that are predicted by SBBN theory with $N_\nu = 3$, $\tau_n = 887$ s, and the nuclear cross sections that were compiled by Caughlan & Fowler (1988) and updated by M. S. Smith et al. (1993) are displayed in Figure 1 for $1 \leq \eta_{10} \leq 10$. They essentially coincide with the results of Smith et al. (1993). Over the range $2 \lesssim \eta_{10} \lesssim 8$, they are well approximated by simple interpolating formulae (maximal deviation smaller than the uncertainty due to the uncertainties in the nuclear cross sections):

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The primordial mass fraction of ^{4}He is well described by

$$Y_p \approx 0.2272 + 0.0105 \ln \eta_{10} - 2([\mathrm{D}]_p + [^3\mathrm{He}]_p)/[\mathrm{H}]_p .$$

The primordial abundances (by number) of D, ^{3}He, and ^{7}Li are well described by

$$[\mathrm{D}]_p/[\mathrm{H}]_p \approx 4.6 \times 10^{-4} \eta_{10}^{-1.67} ,$$

$$[^3\mathrm{He}]_p/[\mathrm{H}]_p \approx 3 \times 10^{-5} \eta_{10}^{-0.50} ,$$

$$[^7\mathrm{Li}]_p/[\mathrm{H}]_p \approx 5.2 \times 10^{-10} \eta_{10}^{-2.43} + 6.3 \times 10^{-12} \eta_{10}^{2.43} .$$

The 1 σ uncertainties in the predicted abundances of ^{4}He, D, ^{3}He, and ^{7}Li due to uncertainties in the nuclear cross sections are 2%, 4%, 6%, and 20%, respectively. [The 20% uncertainty in ^{7}Li is mainly due to the uncertain normalizations of the cross sections for ^{7}Li(p, ^{4}He)^{4}He, ^{3}He(^{4}He, γ)^{7}Be, and ^{4}He(T, γ)^{7}Be.]

3. INFERRED PRIMORDIAL ABUNDANCES

^{4}He.—The most accurate determinations of the primordial abundance of ^{4}He are based on measurements of its recombination radiation in very low metallicity extragalactic H II regions, which are the least contaminated by stellar production of ^{4}He. A number of groups have obtained high-quality data for very metal-poor, extragalactic H II regions which they used to extrapolate to zero metallicity, yielding $Y_p = 0.228 \pm 0.005$ (Pagel et al. 1992), $Y_p = 0.226 \pm 0.005$ (Mathews et al. 1993), $Y_p = 0.230 \pm 0.005$ (Skillman & Kennicutt 1993), and $Y_p = 0.229 \pm 0.004$ (Izotov et al. 1994), where 1 σ statistical and systematic errors were added in quadrature. A weighted average yields

$$Y_p = 0.228 \pm 0.005 . \tag{1}$$

It is not inconceivable that systematic errors (e.g., due to collisional excitation, contribution of neutral helium, interstellar reddening, UV ionizing radiation, grain depletion, nonhomogeneous density, and temperature) are larger. However, there is no empirical evidence for that.

Deuterium.—Deuterium is easily destroyed even at relatively low temperatures. Consequently, its abundance observed today can only provide a lower limit to the big bang production. Measurements of its abundance in the local interstellar medium (LISM) made recently by the *Hubble Space Telescope* (Linsky et al. 1993) gave $[\mathrm{D}]/[\mathrm{H}] = 1.65^{+0.07}_{-0.18} \times 10^{-5}$. From the analysis of solar-wind particles captured in foils exposed on the moon and studies of primitive meteorites, Geiss (1993) deduced a presolar abundance of $[\mathrm{D}]/[\mathrm{H}] = (2.6 \pm 1.0) \times 10^{-5}$. These values can be used as lower bounds on primordial deuterium. High-redshift, low-metallicity quasar absorption systems offer the possibility of observing its abundance in the past in very primitive clouds (Webb 1991). Recent measurements of the absorption spectrum of the distant quasar Q0014+813 in a low-metallicity high-redshift ($z = 3.32$) hydrogen cloud by Songaila et al. (1994) with the Keck 10 m telescope at Mauna Kea, HI, and by Carswell et al. (1994) with the 4 m telescope at Kitt Peak, AZ, showed an absorption line at the expected position of the isotopically shifted Lyα line of deuterium. The line shape was best fitted with a deuterium abundance of

$$[\mathrm{D}]/[\mathrm{H}] = (1.9\text{–}2.5) \times 10^{-4} . \tag{2}$$

(The probability that the absorption line is due to a second hydrogen cloud with a Lyα absorption line at the position of the isotopically shifted deuterium line was estimated as 3% and 15% by Songaila et al. 1994 and Carswell et al. 1994, respectively.) The above value is an order of magnitude larger than the interstellar value and a factor of 3 larger than the 95% confidence level upper bound on the primordial abundance of D + ^{3}He that was inferred by Walker et al. (1991). However,

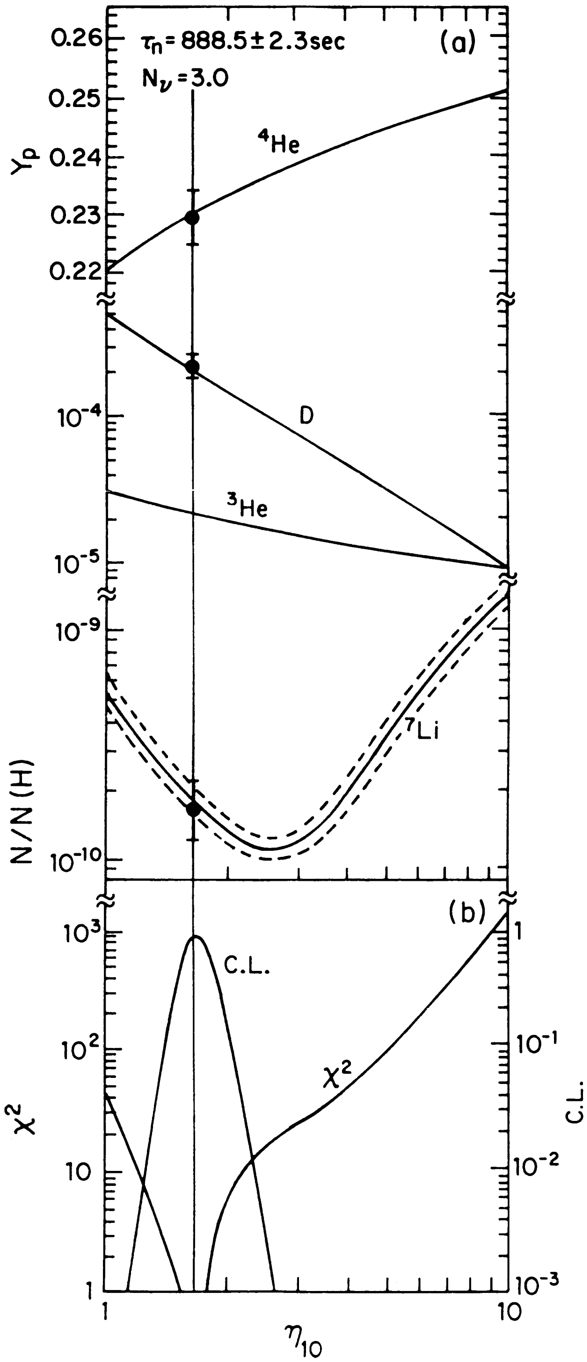

FIG. 1.—(a) Primordial mass fraction of ^{4}He and the abundances (by number) of D, ^{3}He, and ^{7}Li as a function of η_{10} as predicted by SBBN theory. Also shown are their observed values extrapolated to zero age, as summarized in § 3. The vertical line indicates the value $\eta_{10} = 1.6$. (b) Values of χ^2 (*left-hand scale*) and the corresponding confidence level (*right-hand scale*) of the agreement between the predicted abundances and those inferred from observations, as function of η_{10}. Best agreement is obtained for $\eta_{10} \approx 1.60$ with a confidence level above 70%

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Walker et al. (1991) used an uncertain galactic chemical evolution model to extrapolate their estimated presolar D + ^{3}He abundance to zero cosmic age. Moreover, interstellar measurements of D and ^{3}He abundances show large variations from iste to site, and the solar system values may not be a typical sample of Galactic material 4.5 Gyr ago.

^{3}He.—From measurements of [^{3}He]/[^{4}He] in meteorites and the solar wind, Geiss (1993) concluded that the presolar abundance of ^{3}He is $[^3\mathrm{He}]/[\mathrm{H}] = (1.5 \pm 0.3) \times 10^{-5}$. However, any further extrapolations to zero cosmic age of the ^{3}He (or the ^{3}He + D) abundance extracted from solar system or interstellar observations are highly uncertain because ^{3}He is both produced [via $\mathrm{D}(p, \gamma)^3\mathrm{He}$] and destroyed [via $^3\mathrm{He}(^3\mathrm{He}, 2p)^4\mathrm{He}$ and $^4\mathrm{He}(^3\mathrm{He}, \gamma)^7\mathrm{Be}$] in early-generation stars. (Hogan 1994 recently suggested that the envelope material in low-mass stars is mixed down to high temperature after the stars reach the giant branch, so that the ^{3}He is destroyed before the material is ejected.) Indeed, from radio observations of highly ionized Galactic H II regions, Balser et al. (1994) and Wilson & Rood (1994) inferred [^{3}He]/[H] values that ranged between $(6.8 \pm 1.5) \times 10^{-6}$ for W49 and $(4.22 \pm 0.08) \times 10^{-5}$ for W3. Hyperfine emission in the planetary nebula N3242 indicates (Rood, Bania, & Wilson 1992) a large enrichment, $^3\mathrm{He/H} \approx 10^{-3}$. These widely spread values show that the presently observed ^{3}He abundances apparently reflect complicated local chemical evolution and do not allow a reliable determination of the primordial ^{3}He abundance from presently observed solar or LISM abundances.

^{7}Li.—The primordial abundance of ^{7}Li was determined from the most metal-poor Population II halo stars. Such stars, if sufficiently warm ($T \gtrsim 5500$ K), have apparently not depleted their surface lithium and are expected to have a nearly constant ^{7}Li abundance, reflecting its abundance at the early evolution of the Galaxy (Spite & Spite 1982a, b). High-precision Li I observations of 90 extremely metal-poor halo dwarfs and main-sequence turnoff stars have been performed recently by Thorburn (1994). From the surface ^{7}Li abundances of the hottest metal-deficient stars ($T \sim 6400$ K) Thorburn estimated

$$[^7\mathrm{Li}]_p/[\mathrm{H}]_p = (1.7 \pm 0.4) \times 10^{-10} \; . \qquad (3)$$

Thorburn's data suggest a slight systematic variation of the ^{7}Li abundance with surface temperature, possibly indicating some depletion from a higher primordial value by processes that transport ^{7}Li inward to regions where it can be burned. However, the amount of depletion is constrained by the relatively narrow spread in ^{7}Li abundance for a wide range of surface temperatures and metallicities and by the observation of ^{6}Li in Population II stars by Smith, Lambert, & Nissen (1993) and by Thorburn (1994): Big bang production of ^{6}Li is negligible. It is presumably produced by cosmic rays. Since ^{6}Li is burned much more easily than ^{7}Li and yet still observed with the abundance expected for cosmic-ray production, depletion of ^{7}Li cannot have been very significant.

4. COMPARISON BETWEEN THEORY AND OBSERVATIONS

In Figure 1 we compare the predictions of the SBBN theory and the observed abundances of the light elements extrapolated to their primordial values (summarized in § 3). The confidence level of the agreement between the two using the standard χ^2 test as function of η_{10} is also shown in Figure 1. (Errors were assumed to be statistical in nature. Experimental and theoretical uncertainties were added in quadrature.) Figure 1 shows that the primordial abundances of the light elements as inferred from observations are in very good agreement (confidence level higher than 70%) with those predicted by SBBN theory for $\eta_{10} \approx 1.60 \pm 0.1$. The corresponding mean cosmic baryon number density is $n_b = \eta n_\gamma = (6.6 \pm 0.5) \times 10^{-8}\ \mathrm{cm}^{-3}$, which yields a baryon mass density (in critical density units $\rho_c \equiv 3H_0^2/8\pi G$) of

$$\Omega_b \equiv \rho_b/\rho_c = 0.0058 \pm 0.0007\, h^{-2} \qquad (4)$$

and SBBN abundances of $Y_p = 0.230 \pm 0.002$, $[\mathrm{D}]_p/[\mathrm{H}]_p = (2.12 \pm 0.20) \times 10^{-4}$, $[^3\mathrm{He}]_p/[\mathrm{H}]_p = (2.38 \pm 0.08) \times 10^{-5}$, and $[^7\mathrm{Li}]_p/[\mathrm{H}]_p = (1.88 \pm 0.44) \times 10^{-10}$.

5. ARE MOST BARYONS DARK?

Baryons are visible when they form stars or when they emit or absorb electromagnetic radiation in neutral and ionized gas. Most of the visible stars are within the optical radius of galaxies. The mean numbers of galaxies per unit volume with luminosity in the range L to $L + dL$ is well represented by the Schechter luminosity function (Schechter 1976):

$$dn = \phi(L)dL = \phi_*(L/L_*)^\alpha e^{-L/L_*}(dL/L_*) \; , \qquad (5)$$

where ϕ_* is a normalization constant, α is a power parameter and L_* is the luminosity of a typical galaxy. Within their optical radii, the ratios of mass to blue light satisfy approximately the relation

$$(M/L_B) = R_b(M_\odot/L_\odot)(L/L_*)^\beta \; . \qquad (6)$$

Recent measurements (Loveday et al. 1992) gave $\phi_* = (1.40 \pm 0.17) \times 10^{-2}\ L_\odot\ h\ \mathrm{Mpc}^{-3}$, $L_* = (1.21 \pm 0.15) \times 10^{10}\ L_\odot$, and $\alpha = -1.11 \pm 0.15$. The measured mass-to-light ratios within the optical radii of elliptical galaxies (e.g., van der Marel 1991) and for the disk plus bulge of spiral galaxies (e.g., Kent 1988) yield $\beta \approx 0.35 \pm 0.05$ and $R_b = (8 \pm 2)h$. Hence, the mean cosmic densities of luminosity and luminous mass which reside in galaxies are, respectively,

$$\Phi = \phi_*\Gamma(2 + \alpha)L_* = (1.83 \pm 0.35) \times 10^8\, h\, L_\odot\ \mathrm{Mpc}^{-3} \; , \qquad (7)$$

$$\begin{aligned} \rho_L &= \phi_*\Gamma(2 + \sigma + \beta)R_b L_*/L_\odot M_\odot \\ &= (1.23 \pm 0.38) \times 10^9\, h^2\, M_\odot\ \mathrm{Mpc}^{-3} \; , \end{aligned} \qquad (8)$$

yielding

$$\Omega_* = (4.5 \pm 1.4) \times 10^{-3} \qquad (9)$$

similar to the value derived by Peebles 1993, but larger than that derived by Persic & Salucci 1992, who used $R_b = 2.4h$ for spiral galaxies. Note, however, that the above estimate *assumes* that most of the mass within the visible part of galaxies is baryonic.

Most of the observed gas in the present universe is in the form of X-ray–emitting ionized gas in elliptical galaxies and in the intergalactic space within groups and clusters of galaxies. If Ω_{gas} is dominated by Abell richness class 2 clusters, with Coma as typical ($M_{\mathrm{gas}} \approx 1.1 \times 10^{14} h^{-5/2}\ M_\odot$; Hughes 1989; Watt et al. 1992), then a space density of $2.3 \times 10^{-6} h^3\ \mathrm{Mpc}^{-3}$ (Bahcall 1988) implies $\Omega_{\mathrm{gas}} \approx 0.00092 h^{-3/2}$. However, by adding the contributions from gas in poor clusters and in groups, assuming that its mass in these systems is larger than $0.05 h^{-3/2}$ times their total mass (Ponman & Bertram 1993), we arrive at a much larger density of gas, consistent with the following estimate: X-ray studies of clusters with *ROSAT* indicate that the total mass of X-ray–emitting gas in clusters and groups is much larger than the total stellar mass (visible galaxies) and constitutes a fraction of about (Briel et al. 1992; White et al. 1993; White & Fabian 1995) $\langle M_{\mathrm{gas}}/M_t \rangle \approx 0.05 h^{-3/2}$ of the total mass. Numerical simulations (e.g., White et al. 1993) indicate that M_{gas}/M_t has not changed significantly during cluster formation. If the above ratio is typical of the whole universe, then since the average mass-to-light ratio in clusters and groups is $\langle M_t/L \rangle_B \approx 230 \pm 30 h\ M_\odot/L_\odot$ (Bahcall et al. 1994) and since the mean density of light in the universe is $\Phi = (1.83 \pm 0.35) \times 10^8 h\ L_\odot\ \mathrm{Mpc}^{-3}$ (Loveday et al. 1992), therefore the mean gas density in the universe is

$$\Omega_{\mathrm{gas}} \approx \frac{\Phi \langle M_t/L \rangle \langle M_{\mathrm{gas}}/M_t \rangle}{\rho_c} \approx 0.0074 \pm 0.0020 h^{-3/2} . \quad (10)$$

Thus, the mean density of luminous matter, $\Omega_* + \Omega_{\mathrm{gas}}$, is consistent with the mean baryon density derived from SBBN theory if $h = 0.80 \pm 0.17$, as determined from recent measurements (Fukugita et al. 1993; Pierce et al. 1994; Freedman et al. 1994).

6. CONCLUSIONS

The best values of the primordial abundances of the light elements extracted from observations agree very well with the predictions of SBBN theory if $\eta_{10} = 1.6 \pm 0.1$. This value yields a mean baryon mass density, $\Omega_b = (0.0058 \pm 0.0007) h^{-2} \sim 1\%–1.5\%$, consistent with our estimate of the mean cosmic density of luminous matter. Thus, SBBN does not imply that most of the baryons in the universe are dark. Still, a significant fraction of the total baryonic mass may reside in faint stars or invisible low-mass objects which can produce microlensing events like those recently discovered by the MACHO (Alcock et al. 1993), EROS (Aubourg et al. 1993), and OGLE (Udalski et al. 1993) collaborations, but only if $h \ll 0.8$. Since there is dynamical evidence from clusters of galaxies and large-scale structures that the total mass density in the universe satisfies $\Omega \gtrsim 0.10$ (e.g., Peebles 1993 and references therein), SBBN does imply that $\Omega \gg \Omega_b$, i.e., that most of the dark matter in the universe is nonbaryonic.

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