DARK MATTER AND BIG BANG NUCLEOSYNTHESIS

Arnon Dar

Department of Physics and Space Research Institute,
Technion - Israel Institute of Technology, Haifa 32000, Israel

ABSTRACT

The recently observed Deuterium abundance in a low-metallicity high-redshift hydrogen cloud, which is about ten times larger than that observed in the near interstellar medium, is that expected from the Standard Big Bang Nucleosynthesis theory and the observed abundances of $^4$He and $^7$Li extrapolated to their primordial values. The inferred cosmic baryon to photon ratio, $\eta = (1.60 \pm 0.1) \times 10^{-10}$, yields a mean cosmic baryon density, in critical mass units, of $\Omega_b \approx (0.6 \pm 0.1) \times 10^{-2}h^{-2}$, where $h$ is the Hubble constant in units of $100 \ km \ s^{-1} \ Mpc^{-1}$. This baryon density is consistent with the mean cosmic density of matter visible optically and in X-rays. It implies that most of the baryons in the Universe are visible and are not dark. Combined with the observed ratio of baryons to light in X-ray emitting clusters, it yields the value $\Omega \approx 0.15$ for the mean mass density of the Universe, which is consistent with that obtained from the mass to light ratio in clusters. This mass density is about ten times larger than the mean baryon mass density. It indicates that most of the matter in the Universe consists of nonbaryonic dark matter.

* Supported in part by the Technion Fund for Promotion of Research
I. INTRODUCTION The agreement between the predictions of the Standard Big Bang Nucleosynthesis (SBBN) theory (Peebles 1966; Wagoner, Fowler and Hoyle 1967; Wagoner 1973; Yang et al 1984) 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 (e.g., Weinberg 1972; Kolb and Turner 1990; Peebles 1993). The predictions of the SBBN theory depend on low energy nuclear cross sections and on three additional parameters, the number of flavours of light neutrinos, $N_\nu$, the neutron lifetime, $\tau_n$, and the ratio of baryons to photons in the Universe, $\eta \equiv n_b/n_\gamma$. The relevant nuclear cross sections are known from laboratory measurements (e.g., Caughlan and Fowler 1988 and references therein, Smith et al 1993 and references therein). Measurements at the Large Electron Positron Collider (LEP) at CERN gave $N_\nu = 3.04 \pm 0.04$ (e.g., Mana and Martinez 1993). Measurements of $\tau_n$ in neutron bottles and Penning traps coupled with previous measurements yielded the weighted average (see Particle Data Group 1994) $\tau_n = 887 \pm 2.0 \text{ s}$. Finally, measurements of the cosmic microwave background radiation by COBE (Mather et al 1994) gave a blackbody temperature $T = 2.726 \pm 0.017 \text{ K}$, which yields $n_\gamma = 20.28 T^3 \approx 411 \pm 8 \text{ cm}^{-3}$. Hence, the primordial abundances of the light elements are now predicted quite accurately by the SBBN theory as a function of a single unknown parameter, $n_b$, the mean baryon number density in the Universe. The primordial abundances of $^4$He, D, $^3$He and $^7$Li that are predicted by the SBBN theory with $N_\nu = 3$, $\tau_n = 887 \text{ s}$ and the nuclear cross sections that were compiled by Caughlan and Fowler (1988) and updated by Smith et al (1993) are displayed in Fig. 1 for $1 \leq \eta_{10} \leq 10$. Thus, the primordial abundances of the light elements which are inferred from observations, can be used to test the consistency of the hot Big Bang model of the early Universe and to determine the mean baryon density in the Universe.

Indeed, during the past few years it has been claimed repeatedly that the predictions of SBBN theory agree with observations if $\eta_{10} \equiv \eta \times 10^{10} \approx 4$, and that implies that most of the nucleons in the Universe are dark (e.g., Kolb and Turner 1990, Walker et al 1991, Smith et al 1993 and references therein). Moreover, based on these analyses, variety of limits on physics beyond the standard particle physics model (new interactions; new weakly interacting particles; additional neutrino flavours; 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 relied heavily on the highly uncertain extrapolated values for the primordial abundances of D and $^3$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 and Rudzsky 1992).

During the past three 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 and Kennicutt 1993; Izotov et al 1994), \(^7\)Li (Thorburn 1994) and \(^7\)Li (Songaila et al 1994; Carswell et al 1994). In particular, the recent measurements of the absorption spectrum of the distant quasar Q0014+813 in a low-metallicity high-redshift (\(z=3.32\)) intervening hydrogen cloud, by Songaila et al (1994) with the Keck 10m telescope at Mauna Kea, Hawaii, and by Carswell et al (1994) with the 4m telescope at Kit Peak, Arizona show an absorption line whose position coincides with that expected of the isotopically shifted Lyman \(\alpha\) absorption line of deuterium. The best fitted Deuterium abundance is \(1.9 \times 10^{-4} \leq [\text{D}]/[\text{H}] \leq 2.5 \times 10^{-4}\). Below I show (see also Dar 1995a; 1995b) that the above value for the primordial abundance of Deuterium and the best estimated values of the primordial abundances of \(^4\)He and \(^7\)Li which were inferred from observations are in excellent agreement with those predicted by SBBN theory, if the cosmic baryon to photon ratio is \(\eta = (1.60 \pm 0.1) \times 10^{-10}\). This ratio yields a mean cosmic baryon density, in critical mass units, of \(\Omega_b \approx (0.6 \pm 0.1) \times 10^{-2} h^{-2}\), with \(h\) being the Hubble constant in units of \(100 \text{ km s}^{-1} \text{ Mpc}^{-1}\), which is consistent with the mean baryon density of matter visible optically and in X-rays. It implies that (a) most of the baryons in the Universe are visible and are not dark, (b) \(\Omega \approx 0.15\) as inferred also from the mean luminosity density of the Universe and the masses of clusters of galaxies obtained from optical, gravitational lensing and X-ray observations, (c) most of the dark matter in groups and clusters of galaxies is nonbaryonic, (d) most of the matter in the Universe is nonbaryonic dark matter.

III. INFERRED PRIMORDIAL ABUNDANCES

**Helium \(^4\):** The most accurate determinations of the primordial abundance of \(^4\)He are based on measurements of its recombination radiation in very low metallicity extragalactic HII 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 HII 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 and Kennicutt 1993), \(Y_p = 0.232 \pm 0.004\) (Izotov et al 1994), where 1\(\sigma\) statistical and systematic errors were added in quadrature. A weighted average yields

\[
Y_p = 0.229 \pm 0.005. \tag{1}
\]

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, etc.) are larger. However, there is no empirical indication for that.

**Deuterium:** Since Deuterium is easily destroyed at relatively low temperatures, its abundance observed today can only provide a lower limit to the big-bang production. Measurements of the Deuterium abundance in the local interstellar medium (LISM) made recently by the Hubble Space Telescope (Linsky et al. 1993), gave \([\text{D}]/[\text{H}] = (1.65^{+0.07}_{-0.18}) \times 10^{-5}\). From the analysis of solar-wind particles captured in foils exposed on the moon and studies of primitive meteorites, Geiss (1993) deduced a pre-solar Deuterium abundance \([\text{D}]/[\text{H}] = (2.6 \pm 1.0) \times 10^{-5}\). These values can
be used as lower bounds on primordial Deuterium. High-redshift, low-metallicity quasar absorption systems offer the possibility of observing Deuterium abundance back in the past in very primitive clouds (Webb 1991). Recently, Songaila et al (1994) and Carswell et al (1994) detected in a high-redshift, low-metallicity cloud absorption system at $z=3.32$ in the spectrum of the Quasar Q0014+813 with an absorption line at the expected position of the isotopically shifted Ly$\alpha$ line of Deuterium. From fitting the line shape they found a Deuterium abundance of

$$\frac{[D]}{[H]} = (1.9 - 2.5) \times 10^{-4}. \quad (2)$$

The probability that the absorption line is due to a second intervening small hydrogen cloud with the Ly$\alpha$ absorption line at the position of the isotopically shifted deuterium line, (this requires a relative velocity of $82 \ km \ s^{-1}$) was estimated as 3% and 15% by Songaila et al (1994) and by Carswell et al (1994), respectively. Preliminary results by Tytler et al, Carswell et al, and Cowie et al on the $[D/H]$ ratio in absorption systems of other quasars yield a range of values between $2 \times 10^{-5}$ and $2 \times 10^{-4}$. The primordial $[D/H]$ ratio, however, should be obtained by extrapolating the measured values in the most metal poor absorbers to zero metallicity. The above value of $2 \times 10^{-4}$ is an order of magnitude larger than the interstellar value and a factor of three 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, 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, measurements of D and $^3$He abundances in the interstellar space within the Milky Way show large variations from site to site and the solar system values may not be a typical sample of galactic material 4.5 Gyr ago.

**Helium 3:** From measurements of $[^3$He]/[^4He] in meteorites and the solar wind Geiss (1993) concluded that the presolar abundance of $^3$He is $[^3$He]/[H]=$$(1.5 \pm 0.3) \times 10^{-5}$. However, any further extrapolations to zero cosmic age of the $^3$He abundance extracted from solar system or interstellar observations are highly uncertain because $^3$He is both produced [via D(p,$\gamma$)$^3$He] and destroyed [via $^3$He($^3$He,2p)$^4$He] and $^4$He($^3$He,$\gamma$)$^7$Be in early generation stars. (Hogan 1994 has suggested recently that the envelope material in low mass stars is mixed down to high temperature after they reach the giant branch, so that the $^3$He is destroyed before the material is ejected.) Indeed, from radio observations of highly ionized Galactic HII regions Balser et al (1994) and Wilson and Rood (1994) inferred $[^3$He]/[H] values that ranged between $(6.8 \pm 1.5) \times 10^{-6}$ for W49 and $(4.22 \pm 0.08) \times 10^{-5}$ for W3. Hyperfine emission in the planetary nebula N3242 indicates (Rood, Bania and Wilson 1992) a large enrichment $[^3$He]/[H]$$\approx 10^{-3}$. These 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 abundances of either $^3$He or $^3$He+D from presently observed solar or LISM abundances.

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

\[
\frac{[^7\text{Li}]_p}{[\text{H}]_p} = (1.7 \pm 0.4) \times 10^{-10}.
\]

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

IV. COMPARISON BETWEEN THEORY AND OBSERVATIONS

In Fig 1 we compare the predictions of the SBBN theory and the observed abundances of the light elements extrapolated to their primordial values (summarized in section III). The confidence level of the agreement between the two using the standard \(\chi^2\) test as function of \(\eta_{10}\) is also shown in Fig.1. (Errors were assumed to be statistical in nature. Experimental and theoretical uncertainties were added in quadrature). Fig.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 provided that \(\eta_{10} \approx 1.60 \pm 0.1\). The corresponding mean cosmic baryon number density is \(n_b = \eta n_\gamma = (6.6 \pm 0.5) \times 10^{-8} cm^{-3}\), which yields a baryon mass density (in critical density units \(\rho_c \equiv 3H_0^2/8\pi G\) ) of

\[
\Omega_b \equiv \rho_b/\rho_c = (0.6 \pm 0.1) \times 10^{-2} h^{-2}.
\]

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

V. 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):

$$dn = \phi(L)dL = \phi_*(L/L_*)^\alpha e^{-L/L_*}(dL/L_*)$$  \hspace{1cm} (5)$$

where $\phi_*$ is a normalization constant, $\alpha$ is a power parameter and $L_*$ is the luminosity of a typical galaxy. Recent measurements (Loveday et al 1992) gave $\phi_* = (1.40 \pm 0.17) \times 10^{-2} L_\odot h Mpc^{-3}$, $L_* = (1.21 \pm 0.15) \times 10^{10} L_\odot$ and $\alpha = -1.11 \pm 0.15$. About 1/3 of the galaxies are ellipticals and 2/3 are spirals. Within their optical radii, the ratio of mass to blue light of ellipticals can be represented approximately by $(M/L_B) = R(M_\odot/L_\odot)(L/L_*)^{\beta}$ with (e.g., van der Marel 1991) $\beta \approx 0.35 \pm 0.05$.

Consequently for ellipticals, within their optical radius, $<M/L_B> \approx (8 \pm 2)h$. Similarly, for spirals $<M/L_B> \approx (2.4 \pm 0.6)h$ within their optical radius. Hence, the mean cosmic densities of light and mass within the luminous part of galaxies are given, respectively, by

$$\rho_L = \phi_* \Gamma(2+\alpha)L_* = (1.83 \pm 0.35) \times 10^8 h L_\odot Mpc^{-3},$$  \hspace{1cm} (6)$$

$$\rho_* = \phi_* \Gamma(2+\alpha+\beta)RM_\odot L_*/L_\odot = (1.23 \pm 0.38) \times 10^6 h^2 M_\odot Mpc^{-3},$$  \hspace{1cm} (7)$$

yielding $\Omega_* = (0.28 \pm 0.10) \times 10^{-2}$ (similar to the value derived by Persic and Salucci (1992). Note, however, that the luminous part of galaxies may contain as much as 50% dark matter which may be nonbaryonic, i.e., the mean density of baryons in stars may be as small as $\Omega_* = (0.14 \pm 0.05) \times 10^{-2}$.

Recent X-ray observations indicate that clusters and groups of galaxies contain a total mass of intergalactic gas much larger than their total galactic mass (e.g., White et al 1993 and references therein). For instance, whereas in the Milky Way galaxy the ratio of total gas mass to light is $M_{gas}/L_{MW} \approx 4.8 \times 10^9 M_\odot/2.3 \times 10^{10} L_\odot \approx 0.21 M_\odot/L_\odot$, analyses of recent observations with the ROSAT X-ray telescope of the compact group HCG62 and the Coma cluster yielded $M_{gas}/L_B \approx 4.4 \times 10^{11} M_\odot h^{-5/2}/2.4 \times 10^{10} h^{-2} L_\odot \approx 19 h^{-1/2} M_\odot/L_\odot$ within a distance of $0.24 h^{-1} Mpc$ from the center of HCG62 (Ponman et al 1993), and $M_{gas}/L_B \approx (5.45 \pm 0.98) \times 10^{13} M_\odot h^{-5/2}/1.95 \times 10^{12} h^{-2} L_\odot \approx (28 \pm 6) h^{-1/2} M_\odot/L_\odot$ within a distance of $1.5 h^{-1} Mpc$ from the center of the Coma cluster (Briel et al 1992; White et al 1993). These ratios are approximately radius independent because the optical measurements of the velocity dispersion of galaxies in clusters and the X-ray measurements of the temperature profile of the X-ray emitting intracluster gas show that both the galaxies and the intergalactic gas in clusters trace the same potential and have similar velocities and density distributions. If $<M_{gas}/L_B> \approx (23 \pm 5) h^{-1/2}$ for clusters and groups represents well this ratio for the whole Universe, then from the
measured density of blue light in the Universe (see Eq. (6)) we obtain, respectively, the mean cosmic densities of gas and baryons,

$$\Omega_{\text{gas}} = \frac{\rho_L < M_{\text{gas}}/L_B >}{\rho_c} \approx (1.52 \pm 0.45) \times 10^{-2} h^{1/2}, \quad (8)$$

$$\Omega_b = \Omega_{\text{gas}} + \frac{\rho_L < M_*/L_B >}{\rho_c} \approx ([1.52 \pm 0.45] h^{1/2} + 0.28 \pm 0.15) \times 10^{-2}. \quad (9)$$

Recent measurements of the Hubble parameter (e.g. Freedman et al 1994; Pierce et al 1994; Dahle et al 1994) indicate that $h = 0.70 \pm 0.10$, yielding $\Omega_b = (1.5 \pm 0.5) \times 10^{-2}$. This estimated mean density of baryons which are visible optically and in X-rays, is consistent with the mean density of baryons obtained from BBNS, $\Omega_b = (1.2^{+0.5}_{-0.3}) \times 10^{-2}$. Therefore we conclude that BBNS does not provide evidence that most of the baryons are dark.

The argument that a large fraction of baryons are dark (e.g., Kolb and Turner 1991; Walker et al 1991) was based on the extrapolations of the observed abundances of Deuterium in the solar system (e.g., Geiss 1993) and in the local interstellar medium (Linsky et al 1993) to zero age. Its validity requires not only that the primordial abundance of D which was determined from the absorption spectrum of the quasar Q0014+813 is wrong, but also that the primordial abundances of $^4\text{He}$ and $^7\text{Li}$ are much larger than their current best estimated values. Only then a large fraction of the total baryonic mass can be dark. Such baryonic dark matter could reside in low mass stars and brown dwarfs, which can produce microlensing events like those recently discovered by the MACHO (Alcock et al 1993; Sutherland 1995), EROS (Aubourg et al 1993; Moscoso 1995) and OGLE (Udalski et al 1993) collaborations. However, recent measurements with the Hubble Space Telescopes indicate that in the Milky Way very little baryonic mass resides in low mass stars, i.e., that the mass function of stars does not increase suddenly towards low stellar masses (Bahcall et al 1994). Moreover, preliminary analysis of the statistics of microlensing events yields an optical depth for microlensing of LMC stars by dark massive halo objects (MHO) much smaller than that expected if the MW mass within a radius equal to the distance to the LMC was made of MHOs (Alcock et al 1995).

VI. Evidence For Non Baryonic Dark Matter

Rich clusters of galaxies are the largest objects for which total masses can be estimated directly. In fact, the need for astrophysical dark matter was first identified for such systems by Zwicky in 1933.

The total mass enclosed within a distance $R$ from the centers of clusters of galaxies has been determined by three independent methods:

a) From the virial theorem applied to the radial velocities of cluster members assuming that the velocities are distributed isotropically and that light traces mass (see e.g., Peebles 1993).
b) From analyses of the distribution of giant arcs and arclets produced by gravitational lensing of distant galaxies by the gravitating mass in clusters of galaxies. (see e.g., Tyson et al 1990; Tyson 1991; Kaiser and Squires 1993; Smail et al 1994; Soucail, this volume).

c) From the X-ray emission of intergalactic hot gas which is trapped in the deep gravitational potential of rich clusters, under the assumption that the gas is relaxed (see for instance Jones and Forman 1984; Sarazin 1986; Bohringer, this volume; Forman, this volume).

All three methods yield similar results. When coupled with photometric measurements of the light emitted by the galaxies in the clusters they yield (see, e.g., Bohringer, this volume; Forman, this volume) an average total mass to blue light ratio of $< M/L_B > = (230 \pm 30) h M_\odot/L_\odot$. The density of blue light in the Universe was measured (e.g., Loveday et al 1992) to be $\rho_L = (1.83 \pm 0.35) \times 10^8 h Mpc^{-3}$. If the mean M/L ratio for clusters represents well the mean M/L ratio in the Universe then the mean cosmic density is

$$\Omega = \frac{\rho_L < M/L >}{\rho_c} \approx 0.15 \pm 0.3 . \quad (10)$$

This mean cosmic density is larger by more than an order of magnitude than the mean baryon density inferred from SBBN. This difference provides the best observational evidence for non baryonic dark matter. It is also confirmed by the recent observations with the ROSAT X-ray telescope which has been used to determine the total gravitating mass, $M_t$, of clusters and the fraction of that mass which is in the form of X-ray emitting gas, $M_{gas}$, and by photometric measurements of the light emitted by the galaxies in the clusters which have been used to estimate the total “stellar” mass, $M_*$, within the visible part of these galaxies. It was found (e.g., Briel et al 1992; White et al 1993; White and Fabian 1995; Buote and Canizares 1995) that $M_*/M_t \approx 0.01$ and $< M_{gas}/M_t > \approx 0.05 h^{-3/2}$, i.e., the known forms of baryonic matter account only for a small fraction of the total mass of x-ray emitting clusters. If clusters constitute a fair sample of the Universe it implies that most of the matter in the Universe is non baryonic dark matter.

In fact, numerical simulations of structure formation indicate that the ratio of baryonic to non baryonic mass is preserved in cluster formation (e.g., White et al 1993). Consequently, the mean baryonic density deduced from SBBN and the observed baryonic fraction in clusters imply that

$$\Omega \approx \frac{M_t}{M_b} \Omega_b \approx \frac{0.0058 h^{-2}}{0.01 + 0.05 h^{-3/2}} \approx 0.12 \pm 0.2 , \quad (11)$$

in good agreement with the independent estimate from the mass to light ratio of clusters.
It is interesting to note that if the cosmic dark matter consists of massive neutrinos then the neutrino masses satisfy \((\Omega - \Omega_b)\rho_c \approx \Sigma n_\nu m_\nu c^2\), where \(n_\nu = (3/11)n_\gamma \approx 112 \text{ cm}^{-3}\) for each neutrino flavour. Consequently, for \(h = 0.7 \pm 0.1\), one obtains \(\Sigma m_\nu c^2 \approx (12 \pm 3)h^2 \text{ eV} \approx 6 \pm 3 \text{ eV}\). Such massive neutrinos, together with the cluster baryons, can generate in a self consistent way (Tremaine and Gunn 1979) the gravitational potentials within clusters of galaxies as determined from the X-ray measurements, the optical measurements and the gravitational lensing observations.

VI. CONCLUSIONS

The predictions of the SBBN theory and the best values of the primordial abundances of the light elements extracted from observations agree very well if the mean cosmic baryon to photon ratio is \(\eta_{10} \approx 1.6 \pm 0.1\). This value of \(\eta\) yields a mean baryon mass density, \(\Omega_b = (0.6 \pm 0.1) \times 10^{-2}h^{-2} \approx (1.25 \pm 0.45) \times 10^{-2}\), consistent with the best estimated value of matter visible optically and in X-rays \(\Omega_L \approx (1.52 \pm 0.45)h^{1/2} + 0.28 \pm 0.15) \times 10^{-2} \approx (1.5 \pm 0.5) \times 10^{-2}\). Thus, SBBN does not provide evidence that most of the baryons in the Universe are dark. However, SBBN and the baryon mass to light ratio in clusters imply a total mass density of the Universe of \(\Omega_b \approx 0.12 \pm 0.03\), consistent with \(\Omega \approx 0.15 \pm 0.05\), which was derived from the mean mass to light ratio of clusters obtained from optical, X-ray and gravitational lensing observations, and from the observed luminosity density of the Universe. Since \(\Omega \gg \Omega_b\), it implies that most of the matter in the Universe is nonbaryonic dark matter. If the value of the primordial abundance of Deuterium that was inferred from the absorption spectrum of the quasar Q0014+813 is wrong and if its true value is close to that observed in the local interstellar medium, and if the primordial abundance of \(^4\text{He}\) is much larger than its current best estimated value, and if the primordial abundance of \(^7\text{Li}\) is much larger than its current best estimated value, only then can a large fraction of the total baryonic mass reside in low-mass, faint or invisible stars, which can produce microlensing events like those recently discovered by the MACHO (Alcock et al 1993; Sutherland 1995), EROS (Aubourg et al 1993; Moscoso 1995) and OGLE (Udalski et al 1993) collaborations. However, no excess of low mass stars was discovered in deep surveys with the Hubble space telescope, and too few events of microlensed LMC stars were discovered by MACHO and EROS to support this possibility.
REFERENCES

Alcock, C. et al., 1993, Nature, 365, 621
Alcock, C. et al., 1995, PRL, 74, 2867
Aubourg, E. et al., 1993, Nature, 365, 623
Bahcall, J. et al., 1994, ApJ. 435, L51
Bahcall, N.A., 1988, ARA&A, 26, 631
Bahcall, N.A. and Cen, R.Y., 1993, ApJ. 407, L49
Balser, D.S. et al., 1994, ApJ. 430, 667
Bohringer, H. et al., (1994) Nature, 368, 828
Buote, D.A. and Canizares, C.R., 1995, ApJ. (submitted)
Briel, U.G. et al., (1992), A&A, 259, L31
Carswell, R.F. et al., 1994, MNRAS, in press
Caughlan, G.R. and Fowler, W.A., 1988, Atom. and Nucl. Data Tables, 40, 284
Dahle, H. et al., 1994, ApJ. 435, L79
Dar, A., 1995a, NP. B (Proc. Suppl.) 38, 405
Dar, A., 1995b, ApJ. (in press).
Dar, A., Goldberg, J. and Rudzsky M., 1992, Technion preprint Ph-92-01
Eyles, C.J. et al., 1991, ApJ. 376, 23
Freedman, W.L. et al., 1994, Nature, 371, 757
Geiss, J., 1993, in Origin and Evolution of the Elements, eds. N. Prantzos, E.
Vangioni-Flam, and M. Casse, (Cambridge University Press, 1993) p. 89
Hogan, C., 1994, preprint astro-ph/9407038
Hughes, J.P., 1989, ApJ. 337, 21
Izotov, Y., Thuan. X.T. and Lipovetsky, V.A., 1994, ApJ. 435, 647
Jones, C. and Forman, W., 1984, ApJ. 276, 38
Kaiser, N. and Squires, G. 1993, ApJ. 404, 441.
Kolb, R. and Turner, M., 1990, The Early Universe (Addison Wesley-1990)
Linsky, J.L. et al., 1993, ApJ. 402, 694
Loveday, J. et al., 1992, ApJ. 390, 338
Mana, C. and Martinez, M., 1993, NP. B (Suppl.) 31, 163
Mather, J.C. et al., 1994, ApJ., 420, 439
Mathews, G.J. et al., 1993, ApJ., 403, 65
Moscoso, L., 1995, NP. B (Proc. Suppl.) 38, 387
Paczynski, B., 1986, ApJ. 304, 1
Pagel, E.J. et al., 1992, MNRAS, 255, 325
Particle Data Group, 1994, PR, D50, 1173
Peebles, P.J.E., 1966, ApJ. 146, 542
Peebles, P.J.E., 1993, Principles of Physical Cosmology, (Princeton Series in Physics, 1993)
Persic, M. and Salucci, P., MNRAS, 1992, 258, 14p
Pierce, M.J. et al., 1994, Nature, 371, 385
Ponman, T.J. et al., 1993, Nature, 363, 51
Rood, R.T., Bania, T.M., and Wilson, T.L. 1992, Nature, 355, 618
Sarazin, C.L., 1986, RMP, 58, 1
Schechter, P.L., 1976, ApJ. 203, 267
Skillman E.D. and Kennicutt, R.C. Jr., 1993, ApJ. 411, 655
Smail, J., Ellis, R. and Fitchett, M., 1994, MNRAS (in press)
Smith, V.V., Lambert, D.L. and Nissen, P.E., 1993, ApJ. 408, 262
Smith, M.S., Kawano, L.H. and Malaney, R.A., 1993, ApJ. (Suppl.), 85, 219
Songaila, A. et al., 1994, Nature, 368, 599
Spite, M. and Spite, F., 1982a, A&A, 115, 357
Spite, M. and Spite, F., 1982b, Nature, 297, 483
Sutherland, W. et al., 1995, NP. B (Proc. Suppl.) 38, 389
Thorburn, J.A., 1994, ApJ. 421, 318
Tremaine, S. and Gunn, J.E. 1979, PRL, 42, 407
Tyson J.A. et al., 1990, ApJ. 349, L1
Tyson, J.A., 1991, A.I.P. Conf. Proc. 222, 437
Udalski, A., et al., 1993, Acta Astronomica, 43, 289
van der Marel, R.P., MNRAS, 1991, 253, 710
Wagoner, R.V., 1973, ApJ. 179, 343
Wagoner, R.V., Fowler, W.A. and Hoyle, F., 1967, ApJ. 148, 3
Walker, T.P. et al., 1991, ApJ. 376, 51
Watt, M.P. et al., 1992, MNRAS, 258, 738
Webb, J.K., 1991, MNRAS, 250, 657
Weinberg, S., 1972 Gravitation And Cosmology (John Wiley, 1972)
White, S.D.M. et al., 1993, Nature 366, 429
White, D.A. and Fabian, A.C., 1995, MNRAS, 269, 589
Wilson, T.L. and Rood, R.T., 1994, ARA&A, 32, 191
Yang, J. et al., 1984, ApJ. 227, 697

FIGURE CAPTION

Figure 1. (a) The primordial mass fraction of $^4$He and the abundances (by numbers) of D, $^3$He and $^7$Li as a function of $\eta_{10}$ as predicted by SBBN theory. Also shown are their observed values extrapolated to zero age, as summarized in section III. The vertical line indicates the value $\eta_{10} = 1.6$. (b) The values of $\chi^2$ (left scale) and the corresponding confidence level (right scale) of the agreement between the predicted abundances and those inferred from observations, as function of $\eta_{10}$. Best agreement is obtained for $\eta_{10} \approx 1.60$ with a confidence level above 70%.
This figure "fig1-1.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9504082v1
This figure "fig1-2.png" is available in "png" format from:

http://arxiv.org/ps/astro-ph/9504082v1