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ABSENCE OF A LOWER LIMIT ON Ω_b IN INHOMOGENEOUS PRIMORDIAL NUCLEOSYNTHESIS

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ABSTRACT

We show that a class of inhomogeneous big bang nucleosynthesis models exist which yield light-element abundances in agreement with observational constraints for baryon-to-photon ratios significantly smaller than those inferred from standard homogeneous big bang nucleosynthesis (HBBN). These inhomogeneous nucleosynthesis models are characterized by a bimodal distribution of baryons in which some regions have a local baryon-to-photon ratio $\eta \approx 3 \times 10^{-10}$, while the remaining regions are baryon depleted. HBBN scenarios with primordial $(^2\mathrm{H} + {}^3\mathrm{He})/\mathrm{H} \lesssim 9 \times 10^{-5}$ necessarily require that most baryons be in a dark or nonluminous form, although new observations of a possible high deuterium abundance in Lyα clouds may relax this requirement somewhat. The models described here present another way to relax this requirement and can even eliminate any lower bound on the baryon-to-photon ratio.

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

1. INTRODUCTION

In this paper we point out a feature of inhomogeneous primordial nucleosynthesis scenarios which to our knowledge has not been previously emphasized. We show that inhomogeneous big bang nucleosynthesis (IBBN) scenarios could lead to a relaxation of the lower limit on the baryonic fraction of the closure density, Ω_b. This may have important implications for the problem of the "missing" or dark baryons. In what follows we briefly review the problem of the missing baryons. We then discuss IBBN scenarios which have very low Ω_b but which otherwise produce light-element abundance yields in agreement with observations.

1.1. *Luminous Matter*

A lower bound on Ω_b, can be obtained from an estimate of the baryonic content of all luminous objects. The list of objects for this estimate should include spiral and elliptical galaxies, as well as X-ray emitting diffuse intergalactic gas in groups and clusters of galaxies. Additionally, significant amounts of cold hydrogen gas are also observed at high redshift in Lyα clouds and, in principle, one should account for these objects in any estimate of Ω_b. If this gas lies in front of quasars it can be detected through its absorption features (see Wolfe 1988).

The density of baryons in luminous objects can be estimated simply. It is obtained by multiplying the observed luminosity density, $\mathscr{L}$, by a typical "mass-to-light ratio" (M/L) (in units of mass per luminosity). The sum over spiral galaxies, elliptical galaxies, and diffuse intergalactic gas then yields the ratio of the baryon density in luminous objects, ρ_b^{lum}, to the closure density, ρ_c:

$$\Omega_b^{\mathrm{lum}} = \frac{\rho_b^{\mathrm{lum}}}{\rho_c} = \frac{1}{\rho_c} \sum_i \mathscr{L}_i \left(\frac{M}{L}\right)_i . \tag{1}$$

Contributions from Lyα clouds are often excluded from the sum in equation (1). The rationale for this exclusion is that it is not yet clear to what extent baryons in Lyα clouds are eventually incorporated into galaxies and intergalactic gas already accounted for in equation (1).

The luminous baryon content of the universe has been estimated by a number of authors (e.g., Peebles 1971; Gott et al. 1974; Olive et al. 1981; Börner 1988; Hogan 1990; Persic & Salucci 1992). Most estimates of Ω_b^{lum} fall in the interval

$$0.003 \lesssim \Omega_b^{\mathrm{lum}} \lesssim 0.007 . \tag{2}$$

Uncertainties in these estimates reflect uncertainties in both the observed luminosity densities $\mathscr{L}$ and the adopted M/L ratios. Note that the inferred range for Ω_b^{lum} exhibits only a very weak dependence on the Hubble constant.

Persic & Salucci (1992) estimate that the cosmic baryon density could be as small as $\Omega_b^{\mathrm{lum}} \approx 0.003$. These authors argue that Ω_b^{lum} is smaller than previously estimated by as much as a factor of 2 based upon an attempt to account properly for the fact that M/L ratios decline with decreasing galaxy luminosity. It is interesting to note that the estimate by Persic & Salucci (1992) is close to that for the baryon density in Lyα clouds, $\Omega_{\mathrm{Ly}} \approx 0.002$–$0.003$ (Wolfe 1988; Lanzetta et al. 1991). In any case, there seems to be a consensus that the cosmic baryon density in luminous objects cannot be much larger than $\Omega_b^{\mathrm{lum}} \approx 0.01$. This conclusion is independent of the value of the Hubble constant.

1.2. *Standard Homogeneous Big Bang Nucleosynthesis*

Calculations of standard homogeneous big bang nucleosynthesis (HBBN) provide an independent prediction for the baryon content of the universe. Observationally inferred light-element abundances of ^{2}H, ^{3}He, ^{4}He, and ^{7}Li agree well with calculated primordial nucleosynthesis abundance yields whenever $\Omega_b^{\rm HBBN}$ is in a small range of values centered around $\Omega_b^{\rm HBBN} \approx 0.046 h_{50}^{-2}(T_{2.75})^3$ (Wagoner, Fowler, & Hoyle 1967; Wagoner 1973; Schramm & Wagoner 1977; Yang et al. 1984; Krauss & Romanelli 1990; Walker et al. 1991; Smith, Kawano, & Malaney 1993) where h_{50} is the Hubble constant in units of 50 km s^{-1} Mpc^{-1}, and $T_{2.75}$ is the present microwave background temperature in units of 2.75 K. When computational, observational, and nuclear reaction rate uncertainties are taken into account, the allowed range for $\Omega_b^{\rm HBBN}$ is (Smith et al. 1993)

$$0.043 \lesssim \Omega_b^{\rm HBBN} h_{50}^2 (T_{2.75})^{-3} \lesssim 0.056 \, . \qquad (3)$$

Here the lower limit on $\Omega_b^{\rm HBBN}$ arises mainly from deuterium overproduction. Current estimates of the Hubble constant range between $0.8 \lesssim h_{50} \lesssim 1.7$ (see van den Bergh 1989). The present best determination of the microwave background temperature from the *COBE* satellite is 2.726 K ± 0.010 ($T_{2.75} = 0.9912 \pm 0.0036$) (Mather et al. 1994). The weighted mean of the *COBE* measurement with others at wavelengths greater than 1 mm is 2.76 ± 0.010 ($T_{2.75} = 1.004 \pm 0.004$) (Smith et al. 1993). In what follows we will omit the dependence of Ω_b on the rather accurately known cosmic microwave background radiation (CMBR) temperature.

It is clear upon comparison of equations (2) and (3) and from considerations of the value of the Hubble constant, that the baryon density predicted by HBBN is likely to exceed the baryon density inferred from luminous objects by a factor as much as of 10. This would require that the bulk of baryons in the universe be dark. A vexing question in the standard model of cosmology is how most of the baryons come to be in a nonluminous form.

Recently, Songaila et al. (1994) have reported the detection of an isotope-shifted Lyα deuterium absorption line at high redshift along the line of sight to a quasar. They report a deuterium abundance of $1.9 \times 10^{-4} \lesssim (^2{\rm H/H}) \lesssim 2.5 \times 10^{-4}$. If this value is interpreted as a primordial abundance, then it is significantly larger than the previously accepted upper limit on this quantity: $(^2{\rm H} + {}^3{\rm He/H}) \lesssim 9 \times 10^{-5}$ (Smith et al. 1993; Walker et al. 1991). It is not yet clear whether the new number for (^{2}H/H) should be accepted as the primordial abundance, since the probability of a systematic error from an interloper Lyα absorber could be large.

If we take the primordial deuterium abundance to be $1.9 \times 10^{-4} \lesssim (^2{\rm H/H}) \lesssim 2.5 \times 10^{-4}$, then the range of Ω_b inferred from HBBN changes to

$$0.022 \lesssim \Omega_b^{\rm HBBN} h_{50}^2 \lesssim 0.026 \, . \qquad (4)$$

These values of $\Omega_b^{\rm HBBN}$ could be reconciled with $\Omega_b^{\rm lum}$ without demanding that most baryons be dark, as long as the Hubble parameter is large. Note however, that in this case, there may be little or no dark baryons if $\Omega_b^{\rm lum}$ is near the upper end of its observationally inferred range. In this extreme case the kind of inhomogeneities we discuss in this paper are constrained.

1.3. *Dark Baryons*

Several ways of hiding baryons in dark objects have been suggested. However, most of these scenarios have potential drawbacks or can be ruled out by observation. In view of the complexity of the dark matter problem, we will not present a complete discussion here, but rather refer the reader to recent review articles on the subject (Trimble 1987; Hogan 1990; Ashman 1992). Two potential sites for nonluminous baryons are (1) a smooth intergalactic ionized background of baryons which is not incorporated into galaxies at the present epoch and (2) compact objects in galactic halos such as planets, brown dwarfs, white dwarfs, or black holes. An intergalactic baryonic component could, in principle, account for the missing baryons, but this gas would have to be ionized. If the gas were ionized, then it would not be detectable by absorption features in the spectrum of distant galaxies and quasars. However, the temperature of the gas could not exceed $T \sim 10^8$ K, or its X-ray emission would be observable (Peebles 1971).

It is unclear whether compact objects in the halo which may account for the missing baryons could be comprised principally of low-mass stars. The uncertainty is due to a lack of reliable estimates of the luminosity density from such objects (see Richstone et al. 1992; Burrows 1994). In principle, white dwarfs could exist in large numbers in the halo without having been detected. However, this would imply that the initial mass function (IMF) was strongly peaked around 4 $M_\odot$. Otherwise, too many low-mass stars and/or neutron stars would be produced (Ryu, Olive, & Silk 1990). The progenitors of neutron stars would produce heavy elements. Large numbers of neutron stars in the halo might lead to overproduction of heavy elements at an early epoch in the history of the galaxy.

Probably the best candidates for baryonic compact objects in the halo are brown dwarfs with masses $M \lesssim 0.08\ M_\odot$ and/or massive black holes with masses $M \gtrsim 200\ M_\odot$ (Carr, Bond, & Arnett 1984; Carr 1990). Here, black holes count as baryonic dark matter only if they predominantly were formed from baryons and their formation occurred after the epoch of primordial nucleosynthesis. These black holes could not exceed a mass of about $M \approx 10^{6.5}\ M_\odot$, or structures associated with galactic disks would be disrupted (Lacey & Ostriker 1985).

An abundant brown dwarf population requires a sharp increase in the IMF at or below the hydrogen-burning limit, $M \approx 0.08\ M_\odot$. This requirement stems from the desire not to overproduce low-mass, hydrogen-burning stars. In any case, a star formation process which is intrinsically different from that inferred from observations of current star formation regions would be required in order for either brown dwarfs or black holes to be the hiding places for nonluminous baryons.

The recent results of gravitational microlensing experiments (Alcock et al. 1993; Aubourg et al. 1993) may indicate that at least some component of galactic halo dark matter is comprised of condensed objects. However, these experiments are not definitive as to the composition of these objects. For example, these objects may be low-mass baryonic stars or brown dwarfs, but conceivably these objects could be primordial black holes, topological defects, or mass-energy in some other form which does not (or did not) carry significant net baryon number. It seems likely to us, however, that these objects are baryonic. If this turns out to be the case, then astrophysicists are faced with the problem of how baryons get into such condensed objects without violating star formation constraints from galactic chemical evolution and dynamics. If in the future it is determined that the gravitational microlensing objects are either nonbaryonic, or that baryonic microlensing objects constitute only a small fraction of the halo mass, then the question of where the baryons are hidden and our speculations on the role of the IBBN models and the lower limit on Ω_b become relevant.

If the future gravitational microlensing observations infer that there is a dark matter content equivalent to $\Omega^{\rm Halo} \approx 0.03$–$0.07$, then there may be a problem in interpreting this dark matter as baryonic in origin if the primordial deuterium abundance satisfies $1.9 \times 10^{-4} \lesssim (^2{\rm H/H}) \lesssim 2.5 \times 10^{-4}$. If this case, we could conclude that either the objects are not baryonic or the primordial nucleosynthesis process has been influenced significantly by density fluctuations (Gnedin & Ostriker 1992; Cen, Ostriker, & Peebles 1993; Jedamzik & Fuller 1994b).

2. BARYON INHOMOGENEOUS BIG BANG NUCLEOSYNTHESIS

IBBN scenarios were motivated originally by Witten's speculations about a first-order cosmic QCD-phase transition and its effects on the cosmic distribution of baryon number (Witten 1984). Subsequent work on IBBN models has addressed the question of whether there is a way around the HBBN upper limit on Ω_b (Alcock, Fuller, & Mathews 1987; Applegate, Hogan, & Scherrer 1987, 1988; Fuller, Mathews, & Alcock 1988; Kurki-Suonio et al. 1988, 1990; Malaney & Fowler 1988; Boyd & Kajino 1989; Terasawa & Sato 1989a, b, c, 1990; Kajino & Boyd 1990; Kurki-Suonio & Matzner 1989, 1990; Mathews et al. 1990; Mathews, Schramm, & Mayer 1993; Kawano et al. 1991; Jedamzik, Fuller, & Mathews 1994; Thomas et al. 1994). Most recently it has been shown (e.g., Jedamzik et al. 1994) that for spherically condensed fluctuations the upper limit on Ω_b may be virtually unchanged when compared to the upper limit on Ω_b derived from HBBN, depending upon the adopted upper limit to the observed ^{7}Li abundance.

In the present paper, however, we wish to point out that in inhomogeneous nucleosynthesis scenarios at low average baryon-to-photon ratio (corresponding to $\Omega_b < 0.046h_{50}^{-2}$) fluctuations with the right characteristics can yield primordial light-element abundances which agree with observationally inferred limits. Given the right fluctuation characteristics, there is essentially no *lower* limit on Ω_b.

The type of fluctuation in a low average Ω_b universe which shows agreement between calculated light-element abundances and observationally inferred abundance limits is shown schematically in Figure 1. In this figure we show the distribution of baryon-to-photon ratio η as a function of length scale x. The universe is seen to be made up of two distinct environments: (1) high-density regions with local $\eta^h \approx 3 \times 10^{-10}$ and (2) low-density regions with local baryon-to-photon ratio $\eta^l \ll 3 \times 10^{-10}$, so that low-density regions are essentially evacuated of baryons. Agreement between calculated light-element nucleosynthesis yields and observationally inferred abundance limits is attained in these models because the high-density regions have $\eta^h \approx 3 \times 10^{-10}$ (corresponding to $\Omega_b^h \approx 0.046h_{50}^{-2}$), which is the preferred baryon-to-photon ratio in HBBN. Local abundance yields in high-density regions are then indistinguishable from abundance yields resulting from HBBN. Abundance yields averaged over high- and low-density regions will be indistinguishable from abundance yields in HBBN if the fraction of baryons residing in low-density regions is much smaller than the fraction of baryons residing in high-density regions.

Note that in such IBBN scenarios the averaged baryon density, or equivalently $\bar{\Omega}_b$, will be smaller than the preferred HBBN value. Assuming that a volume fraction f_V of the universe is at $\eta \approx 3 \times 10^{-10}$, and approximating the remaining volume fraction $(1 - f_V)$ to be evacuated of baryons, we infer an average baryon density $\bar{\Omega}_b$:

$$\bar{\Omega}_b \approx \Omega_b^{\rm HBBN} f_V \approx 0.046h_{50}^{-2} f_V , \qquad (5)$$

a value which can be much smaller than $\Omega_b^{\rm HBBN} \approx 0.046h_{50}^{-2}$.

2.1. *Constraints from Baryon Diffusion*

Of course, abundance yields resulting from an inhomogeneous baryon distribution, such as that shown in Figure 1, can only match abundance yields of standard homogeneous primordial nucleosynthesis if the effects of diffusive and hydrodynamic damping processes on fluctuations during the nucleosynthesis era are negligible. This requirement implies

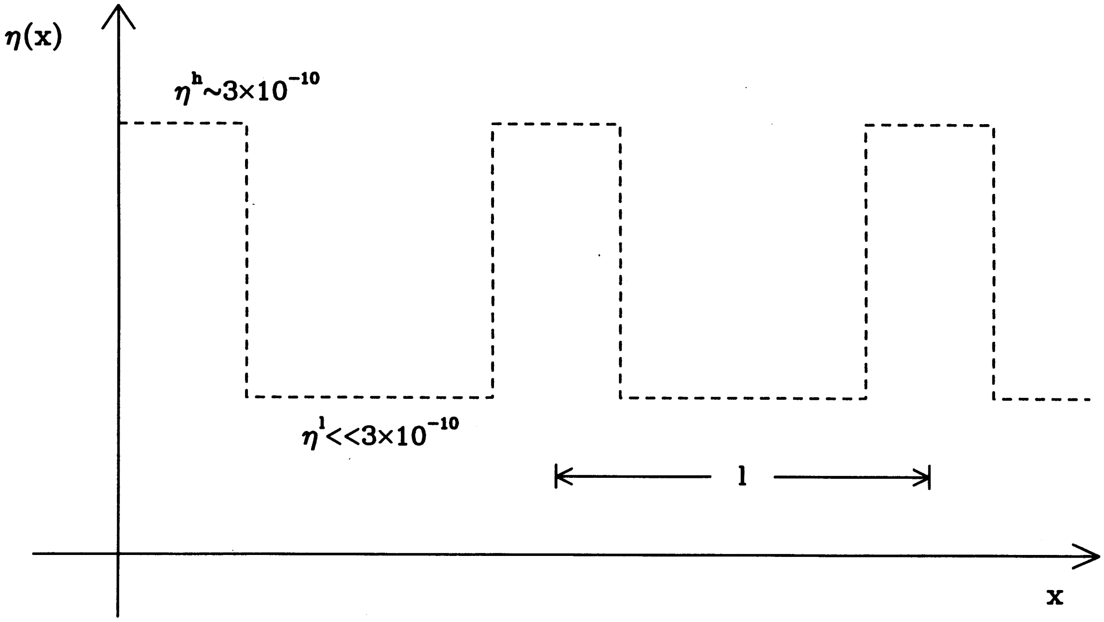

FIG. 1.—The baryon-to-photon ratio η as a function of length coordinate x. We show a bimodal distribution with three high-density regions at $\eta^h \approx 3 \times 10^{-10}$ and low-density regions at $\eta^l \ll 3 \times 10^{-10}$. The mean separation between centers of high-density regions is denoted by l.

that the average mean separation between fluctuation sites l should exceed neutron-, proton-, and photon-diffusion lengths during the epoch of primordial nucleosynthesis. We have calculated the abundance yields of spherically condensed fluctuations with step-function profiles, similar to the fluctuations shown in Figure 1, as a function of fluctuation separation distance l. For this calculation we have assumed a regular lattice of fluctuation sites. We have fixed the baryon-to-photon ratio in the spherical high-density regions at $\eta^h = 3.1 \times 10^{-10}$ and the baryon-to-photon ratio in the low-density regions at $\eta^l = 3.1 \times 10^{-15}$. By assuming a volume fraction $f_V = 0.065$ of the universe to be at high baryon-to-photon ratio, we fix the average Ω_b in our model at $\bar{\Omega}_b = 0.003h_{50}^{-2}$ agreement with the lower limit on Ω_b^{lum}. In Figure 2 we show the calculated abundance yields for ^{2}H plus ^{3}He, ^{4}He, and ^{7}Li resulting from such fluctuations as a function of separation distance between adjacent fluctuation sites l_{100}. Here l_{100} is the proper fluctuation separation distance at an epoch where the cosmic temperature is $T = 100$ MeV. It is evident from the figure that for $l_{100} \gtrsim 10^4$ m, abundance yields in our model with $\bar{\Omega}_b = 0.003h_{50}^{-2}$ are indistinguishable from the abundance yields of a homogeneous primordial nucleosynthesis scenario with $\Omega_b = 0.046h_{50}^{-2}$.

For values of l_{100} smaller than $l_{100} \approx 10^4$ m, deuterium production increases and ^{4}He production decreases. This results from neutron diffusion effecting a transfer from the high-density region to the low-density region. In turn, this diffusive transport leads to the formation of extended transition regions between high- and low-density regimes. The result may be a nonnegligible fraction of baryons at low baryon-to-photon ratio and concomitant overproduction of deuterium. Deuterium yields increase rapidly with decreasing baryon-to-photon ratio.

It is therefore necessary that the separation of high-density regions exceed $l_{100} \gtrsim 10^4$ m in order that deuterium overproduction be avoided. The value of this lower limit on l_{100} may be slightly increased if other fluctuation geometries are considered. Examples of such alternative geometries include high-density spherical shells. A characteristic baryonic mass content can be assigned to the fluctuation cells. For a fluctuation cell of radius $l_{100} \gtrsim 10^4$ m we find that the baryonic mass within each high-density region must exceed

$$M_b \gtrsim 10^{-11}\, M_\odot \left(\frac{l_{100}}{10^4\ \mathrm{m}}\right)^3 \left(\frac{\Omega_b h_{50}^2}{0.003}\right), \qquad (6)$$

in order to avoid deuterium overproduction.

We can compute light-element abundance yields for a universe with baryon-to-photon fluctuations by simply averaging over the HBBN results from different regions with different baryon-to-photon ratios when the mass scale of individual fluctuations exceeds approximately $M_b^{\mathrm{diff}} \gtrsim 10^{-11}\, M_\odot$. It is a common misconception that this mass scale is of the same order as the baryon mass within the horizon during the nucleosynthesis epoch. In fact, the baryonic horizon mass at $T \sim 100$ keV is roughly $M_b^H \sim 1\, M_\odot$, which is 11 orders of magnitude larger than M_b^{diff}. This is because the baryonic horizon mass is determined by $M_b^H \sim (4\pi/3)\bar{\rho}(ct)^3$, with $\bar{\rho}$ the average baryon mass density and (ct) the Hubble length at the epoch with temperature $T \approx 100$ keV. The scale M_b^{diff}, in contrast, is determined by $M_b^{\mathrm{diff}} \sim (4\pi/3)\bar{\rho}d^3$, where d is the neutron diffusion length at the approximate completion of the primordial nucleosynthesis process at $T \approx 100$ keV (Jedamzik & Fuller 1994a).

An upper limit on the baryonic mass of such fluctuations can be obtained from considerations of the small-scale isotropy of the cosmic microwave background radiation (CMBR). It is known that the anisotropies in the CMBR on small angular scales of 1′–10′ do not exceed $\Delta T/T \lesssim 5 \times 10^{-5}$ (Readhead et al. 1989). A fluctuation at baryon-to-photon ratio $\eta \approx 3 \times 10^{-10}$ subtending an angular scale of 1′ at decoupling will contain approximately a baryonic mass of $M_b \approx 10^{11}\, M_\odot$. Such large fluctuations will maintain an increased internal temperature, so that the fluctuation's self-gravity is counterbalanced by the radiation overpressure. In order for the resulting distortions in the CMBR not to exceed the upper limit of $\Delta T/T \lesssim 5 \times 10^{-5}$ on arcminute scales, the baryonic mass within a fluctuation cell has to be less than

$$M_b \lesssim 10^{11}\, M_\odot\,. \qquad (7)$$

Note that the mass scale corresponding to this limit is roughly the baryonic mass of a typical galaxy and is many orders of magnitude above the lower limit given in equation (6).

It has been shown by Gisler, Harrison, & Rees (1974) that the existence of moderate curvature fluctuations during the epoch of primordial nucleosynthesis can have significant effects on the light-element abundance yields. However, the type of fluctuation considered here, even when of superhorizon scale during the nucleosynthesis epoch, has only negligible effects on the curvature. This is because (1) the mass density within baryons is very small compared to the radiation energy density during the nucleosynthesis epoch and (2) our assumption that fluctuations are isothermal on superhorizon scales.

Deuterium overproduction also can be employed to place limits on the fraction of baryons contained in the low-density regions. Likewise, the fraction of baryons residing in transition regions between high- and low-density regimes can be constrained. The total deuterium yield resulting from a bimodal distribution such as the one displayed in Figure 1 (i.e., a distribution without any transition region) is approximately

$$\left(\frac{\bar{D}}{H}\right) \approx \left(\frac{D}{H}\right)_h + f_l\left(\frac{D}{H}\right)_l, \qquad (8)$$

where f_l is the fraction of baryons contained in the low-density regions, and $(\mathrm{D/H})_h$ and $(\mathrm{D/H})_l$ are the local deuterium-to-hydrogen number fractions in high-density and low-density regions, respectively. In writing equation (8) we have implicitly assumed that effects of neutron diffusion during the nucleosynthesis era are negligible and that the fraction of baryons residing in the low-density regions is small, $f_l \ll 1$. The deuterium yield increases at lower baryon-to-photon ratio from $(\mathrm{D/H}) \approx 5.5 \times 10^{-3}$ at $\eta = 10^{-11}$ to a maximum yield of $(\mathrm{D/H}) \approx 9 \times 10^{-3}$ at $\eta = 2 \times 10^{-12}$ and then decreases to $(\mathrm{D/H}) \approx 10^{-3}$ for $\eta = 10^{-13}$. Thus, even a small fraction of baryons residing in the low-density regions could make a significant contribution to the total deuterium abundance. If we require the contribution to the deuterium yield arising from the low-density regions not to exceed $f_l(\mathrm{D/H})_l \lesssim 10^{-5}$, and assume deuterium production in the low-density region to be at a level of $(\mathrm{D/H})_l \approx 10^{-3}$, we obtain an upper limit on the fraction of baryons allowed to reside in the low-density regions, $f_l \lesssim 0.01$. For a universe with $\eta_h = 3.1 \times 10^{-10}$, $f_v = 0.065$, and $\bar{\Omega}_b = 0.003h_{50}^{-2}$ as above, this would imply that the baryon-to-photon ratio in the low-density region should not exceed $\eta_l \lesssim 10^{-13}$. In a similar way, the fraction of baryons within transition regions can be constrained to be smaller than $f_l \lesssim$ 0.01–0.001.

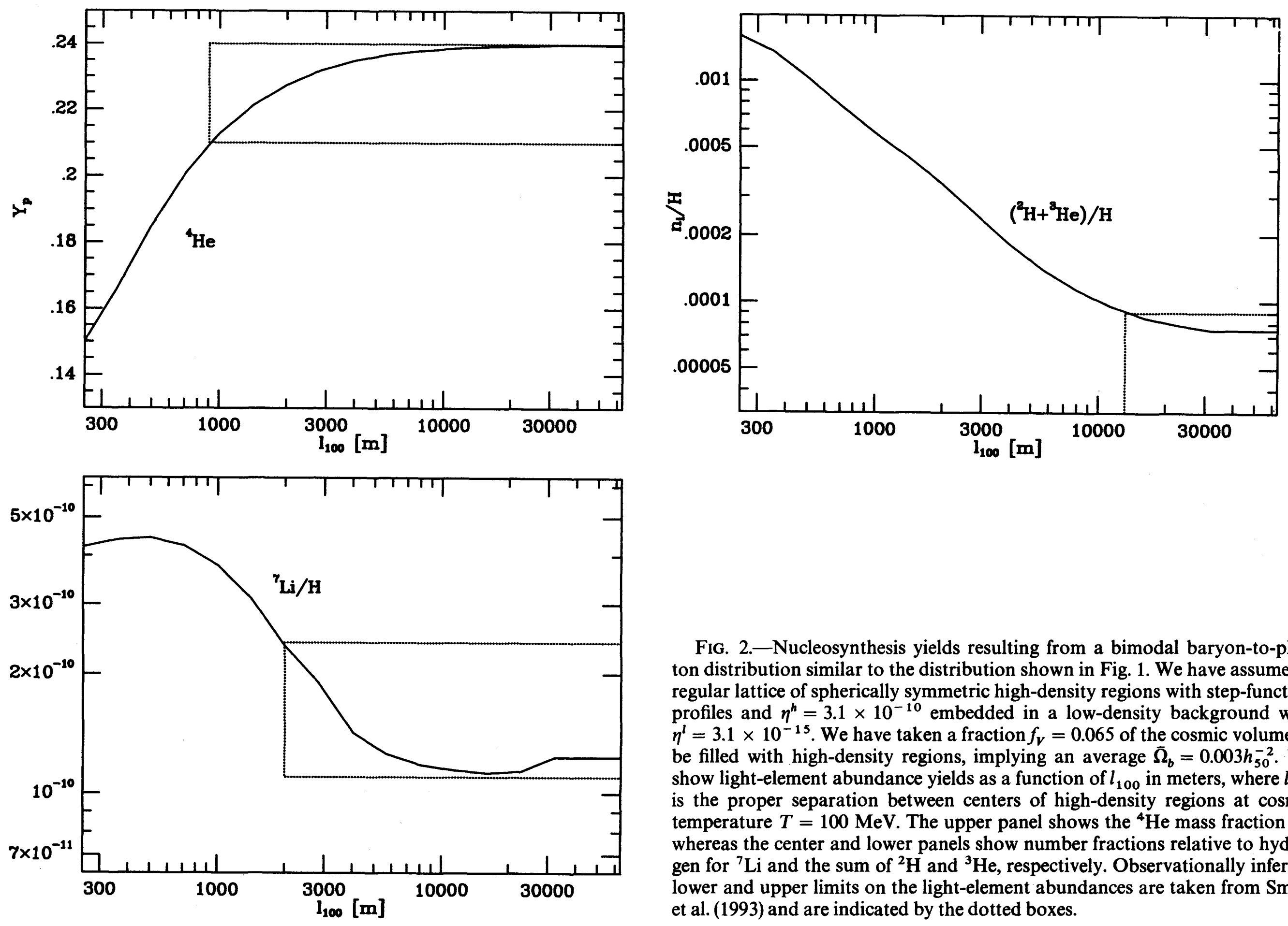

FIG. 2.—Nucleosynthesis yields resulting from a bimodal baryon-to-photon distribution similar to the distribution shown in Fig. 1. We have assumed a regular lattice of spherically symmetric high-density regions with step-function profiles and $\eta^h = 3.1 \times 10^{-10}$ embedded in a low-density background with $\eta^l = 3.1 \times 10^{-15}$. We have taken a fraction $f_V = 0.065$ of the cosmic volume to be filled with high-density regions, implying an average $\bar{\Omega}_b = 0.003 h_{50}^{-2}$. We show light-element abundance yields as a function of l_{100} in meters, where l_{100} is the proper separation between centers of high-density regions at cosmic temperature $T = 100$ MeV. The upper panel shows the ^{4}He mass fraction Y_p, whereas the center and lower panels show number fractions relative to hydrogen for ^{7}Li and the sum of ^{2}H and ^{3}He, respectively. Observationally inferred lower and upper limits on the light-element abundances are taken from Smith et al. (1993) and are indicated by the dotted boxes.

The reader might conclude at this point that it is not surprising that light-element nucleosynthesis can be made to agree with observation for a given Ω_b because there are many adjustable parameters in IBBN models. However, detailed numerical hydrodynamic studies of IBBN scenarios (see Jedamzik et al. 1994) show how remarkably difficult it is to obtain agreement with observations for baryon-to-photon ratios which substantially deviate from $\eta \approx 3 \times 10^{-10}$. However, even though observationally inferred primordial abundance constraints demand that almost all baryons must freeze out of nuclear statistical equilibrium with $\eta \approx 3 \times 10^{-10}$, these same constraints do not limit the fraction of space that is filled by baryons.

Finally, we note that, even for a homogeneous distribution of baryons at cosmic temperature $T \approx 100$ keV, the inferred Ω_b can conceivably be lower than that deduced from a standard cosmic scenario. This can be the case if, after a standard HBBN scenario with $\eta \approx 3 \times 10^{-10}$, a large amount of entropy is released into the CMBR. Such a release of entropy could result in a prolonged ionization or reionization of the universe and would reset the ultimate baryon-to-photon ratio to a lower value. Possible sources of significant entropy production after the epoch of primordial nucleosynthesis could be an abundant primordial black hole population which evaporated well before the present epoch, late-phase transitions or the accretion of matter on an abundant early population of massive black holes. However, there should exist stringent constraints on such scenarios, since the evaporation of primordial black holes and/or the accretion of matter on massive black holes would result in the production of γ-rays, which in turn might reprocess the nuclear abundances by photodisintegration (Carlson et al. 1990; Gnedin & Ostriker 1992). Furthermore, a significant release of entropy could distort the CMBR such that the resulting CMBR spectrum would deviate from a Plankian spectrum (Mather et al. 1990, 1994).

3. CONCLUSIONS

We have shown that there exist IBBN models which agree with observations and which have low values of Ω_b. However, forming the fluctuations to give this result may be problematic. In particular, a lower limit on the baryonic mass of fluctuations of $M_b \gtrsim 10^{-11}\ M_\odot$ implies that a speculative inhomogeneous electroweak baryogenesis scenario (Fuller et al. 1994) cannot form the type of inhomogeneity considered here, as the baryonic mass contained within the horizon during the electroweak epoch is only $\sim 10^{-18}\ M_\odot$. The baryonic mass within the horizon at the QCD epoch, however, is roughly $M_b^{\mathrm{QCD}} \sim 10^{-9}\ M_\odot$, which is close to the lower limit on the mass of fluctuations in equation (6). Only an unlikely first-order QCD-phase transition scenario in which there are a few fluctuations (or nucleation sites) per horizon volume could lead to the formation of a fluctuation with these characteristics. In the framework of a standard early universe scenario, baryogenesis associated with an inflationary epoch could, in principle, form fluctuations on the desired spatial scales. Fluctuations would have to be formed with a bimodal character, with high-density regions having little spread around the baryon-to-photon ratio $\eta \approx 3 \times 10^{-10}$ and baryon-poor low-density regions. Furthermore, the transition regions between high- and low-density should contain only a small fraction of the baryons.

In summary, we have identified and constrained inhomogeneous primordial nucleosynthesis scenarios with abundance yields which agree with observationally inferred abundance limits yet have Ω_b much lower than the lower limit on this quantity from HBBN. These models assume that the universe is filled with high-density regions with $\eta \approx 3.1 \times 10^{-10}$ and low-density regions with $\eta \lesssim 10^{-13}$. A lower limit on Ω_b in these models is completely absent. Such primordial nucleosynthesis scenarios offer an alternative solution to the problem of the missing or dark baryons.

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