NUCLEOSYNTHESIS IN A BARYON-INHOMOGENEOUS UNIVERSE WITH COUPLED BARYON DIFFUSION

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Detailed calculations of big-bang nucleosynthesis in baryon-inhomogeneous universes show that Ω_b can be considerably larger than its limit from standard big-bang nucleosynthesis. Such results require that late-time hydrodynamic effects deplete overproduction of ^7Li and that the QCD surface tension be near the cube of the QCD coexistence temperature for fluctuations of the correct length scales to arise.

1. FIRST ORDER QCD PHASE TRANSITION AND BARYON FLUCTUATIONS

During a first order QCD phase transition, the baryon chemical potentials in the quark and hadron phases will be equal. Because of the large mass of the baryons in the hadron phase, a substantial free-energy penalty must be paid to place a unit of baryon number in the hadron phase. No such penalty is paid in the quark phase, however. The consequence is that baryon number is more "soluble" in the quark phase and that a first order cosmic QCD phase transition could have produced inhomogeneities in the distribution of baryons in the early universe. Such was the initial suggestion of Witten[1], although the relics that he proposed should exist (strange matter nuggets and long wavelength radiation) probably were not produced[2].

The astrophysical consequence of baryon inhomogeneity in the early universe that has generated the most interest has been the possible modifications that could have been made to big-bang nucleosynthesis. Applegate and Hogan[3] were the first to realize that after weak decoupling ($T \sim 1\ MeV$) neutrons and protons would have different diffusive mean free paths in the thermal bath of electrons, positrons, and photons. Neutrons would diffuse out of the high baryon density regions more readily than the protons; therefore, at the beginning of nucleosynthesis ($T \sim 100\ keV$), high-density, proton-rich regions and lower-density, neutron-rich regions would exist. Initial calculations[4] of the nucleosynthesis in these cosmologies showed results considerably different from those in baryon-homogeneous universes.

The most dramatic consequence of these initial nucleosynthesis calculations was that certain ranges of parameters characterizing the amplitude and length scale of the baryon fluctuations allowed Ω_b, the ratio of the present baryon density to the critical density of the universe, to be as high as unity, in contrast to the results from the standard, homogeneous big-bang nucleosynthesis results $0.01 \leq \Omega_b \leq 0.15$[5]. Because inflation suggests $\Omega = 1$ precisely, an Ω_b of unity would indicate that all of the dark matter of the universe is baryonic and that there is no need to invoke the existence of exotic particles such as axions, WIMPs, or massive neutrinos to close the universe.

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2. DETAILED NUCLEOSYNTHESIS CALCULATIONS

It is easy to understand why baryon-inhomogeneous cosmologies allow Ω_b to be larger than in baryon-homogeneous ones. In an $\Omega_b = 1$ homogeneous universe, the high baryon density allows efficient burning of neutrons and protons through deuterium up to ^4He. The result is overproduction of ^4He and underproduction of D compared with observational constraints. In a baryon-inhomogeneous $\Omega_b = 1$ universe, however, this burning is less efficient. In the proton-rich regions, there are relatively fewer neutrons around, while in the neutron-rich regions the lack of protons means the burning must wait until neutrons have decayed into protons ($\tau_{1/2} \approx 10.3\ min$). At later times, when enough neutrons have decayed, the temperature is lower and the subsequent burning of deuterium is less efficient than in the homogeneous case. The net result is that relatively less ^4He is made in both neutron and proton-rich regions and relatively greater amounts of deuterium are made in the neutron-rich regions. The calculated abundances are then in agreement with observational constraints for higher values of Ω_b.

^7Li proved to be relatively overproduced in nearly all the initial calculations of baryon-inhomogeneous nucleosynthesis. This is due to the fact that ^7Li is made both as ^7Be in the proton-rich regions (^7Be later decays via positron emission to ^7Li) and as ^7Li in the neutron-rich regions. Although the deciphering of the primordial ^7Li abundance from observational abundances in old stars is fraught with difficulties[6], the overproduction of ^7Li in the baryon-inhomogeneous universes was large enough that it was deemed necessary to find some means of destroying it.

Malaney and Fowler[7] pointed out that diffusion of neutrons back into the proton-rich regions could destroy much of the ^7Be there via $^7Be(n,p)^7Li(p,\alpha)^4He$. This was one of the primary motivations for the development of detailed nucleosynthesis codes which treat nucleosynthesis and diffusion simultaneously. Three groups have developed such codes, Kurki-Suonio and co-workers[8], Terasawa and Sato[9], and the Livermore group[10]. The results from these codes are in general agreement. We will discuss the results of the last group.

Detailed discussion of the methods and results of the Livermore code may be found in reference 10. The code begins with a spherically condensed, isothermal, baryon fluctuation in a Wigner-Seitz cell of radius r. The fractional volume taken up by the high density region is f_v, while the ratio of the densities in the high density to low density region is R. The evolution of the fluctuation through diffusion and nucleosynthesis is followed from $T = 10^{11}\ K$ to $T = 10^6\ K$. Since diffusion and nucleosynthesis timescales can be comparable or very different, the code couples the diffusion and nucleosynthesis in a completely implicit scheme.

Nucleosynthesis results were obtained for a large range of r, f_v, and R. The optimal results for large Ω_b were for narrow, high-density-contrast fluctuations, in particular, for $r = 50\ m$ (at $T = 100\ MeV$), $f_v^{1/3} = 0.25$, and $R = 10^6$. The nucleosynthesis yields for these fluctuations over a range on Ω_b are shown in fig. 1. The homogeneous results are also shown for constrast. As discussed, ^4He production is down while D production is up, compared to the standard big-bang results. The boxes indicate agreement with observational constraints. From the ^4He and D results, Ω_b can be as large as 0.8 in a baryon-inhomogeneous universe. ^3He results indicate $\Omega_b \leq 0.4$, although this constraint is uncertain due to ^3He production in stars.[5] ^7Li is still overproduced by a fairly large amount.

3. COMPLICATIONS

Alcock *et al.*[11] have shown that at late times (at $T \sim 20\ keV$), when the mean free path of photons has become longer than the length scale of the high density regions, rapid hydrodynamic dissipation of the high density regions may occur. A reverse Malaney-Fowler effect thus occurs by driving ^7Be in the high density regions out into the neutron-rich regions. The authors in reference 11 found in simple models up to two orders of magnitude of destruction of ^7Li from this effect, which may relieve the overproduction of ^7Li problem. Much more detailed work needs to be done on this question, however, before any definitive conclusions can be made.

Another complication is that the universe certainly did not consist of baryon fluctuations sitting at unique separations from each other. Meyer *et al.*[12] have computed the distribution of nucleation-site separations expected to result in the small supercooling limit of the classical nucleation scenario. If a duality is then assumed between nucleation sites and baryon fluctuations, the same distribution may be used to describe the distribution of fluctuation separations. The authors in reference 12 found that when they averaged the results of reference 10 over this distribution, their limit on Ω_b of 0.8 from the ^4He yields dropped to 0.59. Moreover, they found that in order to get $\Omega_b \geq 0.15$, the upper limit from standard big-bang nucleosynthesis, they required σ, the QCD surface tension, to be nearly equal to T_c^3, where T_c is the coexistence temperature of the quark and hadron phases. Recent lattice gauge results indicate that this is near the upper limit on σ.

A third complication has been pointed out by Adams and Freese[13] concerning the relation between nucleation sites and baryon fluctuations. In some cases growing hadron bubbles may become unstable to dendritic growth. The result will be that baryon-fluctuation length scales will be related to the nucleation-site length scales in a complicated way. In fact, dendritic instability may result in such short length scales that diffusion homogenizes the universe well before nucleosynthesis. These questions will only be resolved when detailed models of the phase transition are made and studied.

4. SUMMARY

At present it seems difficult to close the universe with baryons. Ω_b may be larger than 0.15, the upper limit from standard big-bang nucleosynthesis, however, if the QCD surface

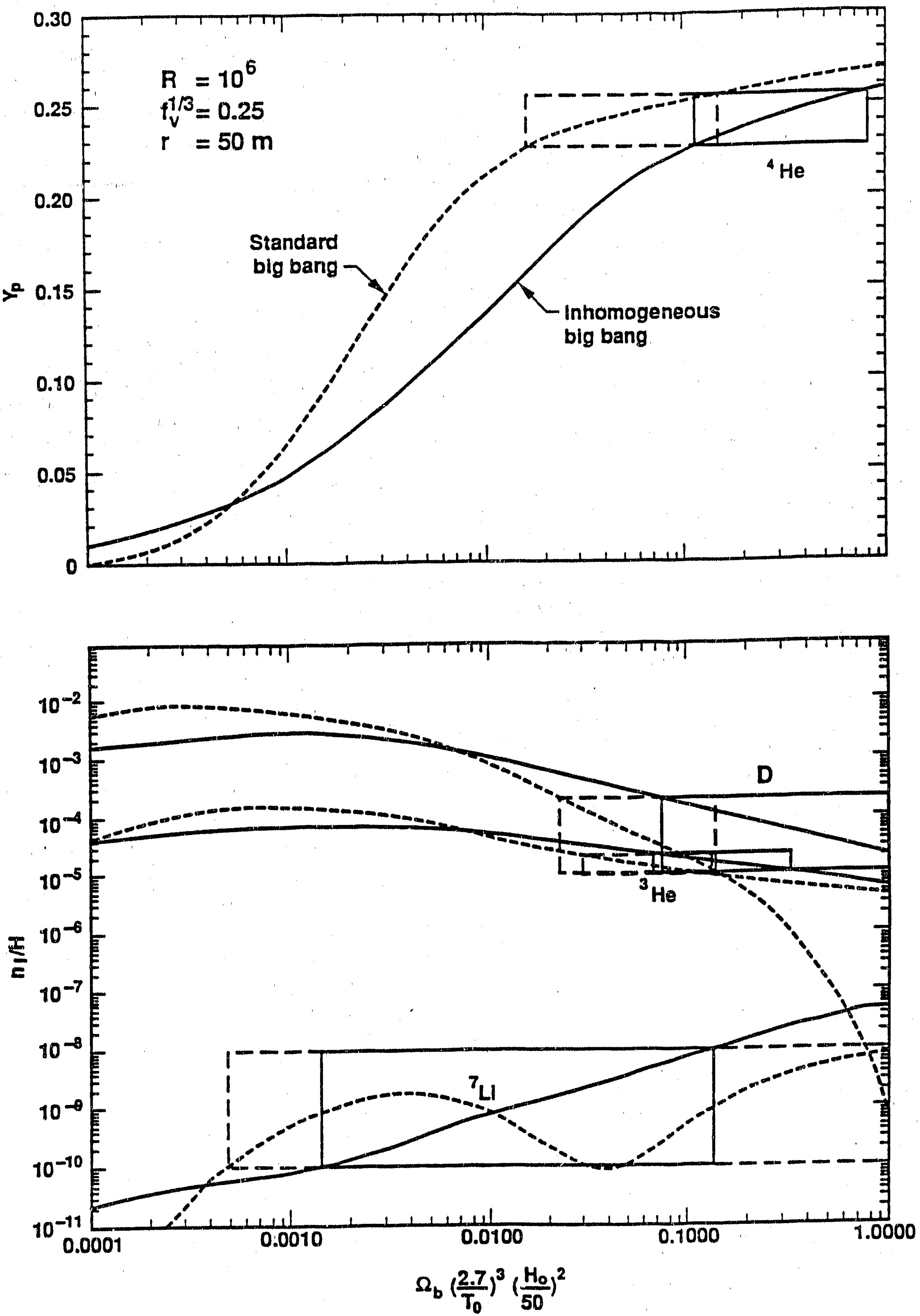

FIGURE 1

Calculated big-bang nucleosynthesis yields in baryon-inhomogeneous and homogeneous universes for a present background radiation temperature of $T_0 = 2.7\ K$ and a Hubble constant of $H_0 = 50\ km/s/Mpc$.

tension is near the cube of the QCD coexistence temperature and if late-time hydrodynamic effects can substantially deplete the ^7Li produced in baryon-inhomogeneous universes.

In light of all of the unknown physics surrounding discussion of nucleosynthesis in baryon-inhomogeneous universes, it would be nice to find some clear-cut nucleosynthetic signature, such as high ^9Be production[14] or a primordial r-process[15], whose observation could confirm or rule out inhomogeneity in the early universe. Such a signature does not seem to be forthcoming, however, so further progress will probably be made only by resolution of the outstanding problems alluded to in section 3.

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