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PRIMORDIAL NUCLEOSYNTHESIS OF INTERMEDIATE-MASS ELEMENTS IN BARYON-NUMBER–INHOMOGENEOUS BIG BANG MODELS: OBSERVATIONAL TESTS

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ABSTRACT

We discuss the primordial nucleosynthesis of intermediate-mass nuclei up to $A = 28$ in the neutron-rich and proton-rich environments produced by baryon-number–inhomogeneous big bang models. We find that there could be several observational signatures of such neutron-rich and proton-rich primordial nucleosynthesis if sufficiently accurate isotopic and elemental abundance ratios could be measured for extremely metal-poor stars. These observations could also provide important information about the degree of baryon-number inhomogeneity at the time of primordial nucleosynthesis.

Subject headings: abundances — early universe — nucleosynthesis — stars: abundances — stars: Population II

I. INTRODUCTION

Recently, in a series of papers (Applegate, Hogan, and Scherrer 1987, 1988; Alcock, Fuller, and Mathews 1987; Audouze, *et al.* 1988; Fuller, Mathews, and Alcock 1988; Kurki-Suonio and Matzner 1989; Malaney and Fowler 1988; Kurki-Suonio *et al.* 1988, 1990; Terasawa and Sato 1989; Mathews *et al.* 1989, 1990), it has been suggested that isothermal baryon number density fluctuations produced by an earlier epoch during the big bang may dramatically affect the yields from primordial nucleosynthesis. The nucleosynthesis is changed by the spatial variation of both the baryon-to-photon ratio and the neutron-to-proton ratio, the latter being caused by the short diffusion time for neutrons in the primordial plasma. These effects change the sensitivity of the nucleosynthetic yields to the average baryon density and may allow (Applegate, Hogan, and Scherrer 1987; Alcock, Fuller, and Mathews 1987) baryonic densities considerably larger than the limit to the baryonic contribution to the closure density of $\Omega_b \lesssim 0.1$ derived from the comparison of observed (light-element) abundances with results from standard homogeneous big bang models (e.g., Yang *et al.* 1984). This increase in the allowed baryon density in inhomogeneous big bang models is caused by the existence of low–baryon-density, extremely neutron-rich regions in which deuterium is synthesized and high-density proton-rich regions which are prevented from overproducing ^{4}He due to a scarcity of neutrons.

Another possible consequence of forming such neutron-rich and proton-rich regions is that intermediate-mass ($12 \leq A \leq 28$) and heavy ($A > 28$) elements may be formed by neutron-capture or proton- and alpha-capture chains (Applegate, Hogan, and Scherrer 1987, 1988; Malaney and Fowler 1988; Mathews *et al.* 1990). This is an intriguing possibility, for two reasons. First, intermediate-mass and heavy-element synthesis may provide an observational constraint on such inhomogeneous cosmologies. Low-metallicity stars may have atmospheres which reflect little or no nuclear processing, so that the observed elemental abundances represent the composition of primordial material. Although there are no zero-metallicity stars known, there are Population II stars with heavy-element abundances significantly lower than solar (e.g., Gilroy *et al.* 1988). It is imperative, therefore, that inhomogeneous cosmological models which satisfy the light-element abundance constraints do not at the same time overproduce the heavy-element abundances of such metal-poor stars.

Yet another important possible consequence of an inhomogeneous big bang may be the existence of unique nucleosynthetic signatures. Among the possible observable signatures of a baryon-number–inhomogeneous big bang already pointed out in previous works are the presence of a high primordial lithium abundance (Alcock, Fuller, and Mathews 1987) or a high abundance of ^{9}Be, ^{10}B, and ^{11}B (Boyd and Kajino 1989; Malaney and Fowler 1989; Kajino and Boyd 1990; Terasawa and Sato 1990). However, the light-element signatures of primordial inhomogeneities are problematic because of possible hydrodynamic effects (Alcock *et al.* 1990). In the present work we explore the possibility of other nucleosynthetic signatures in intermediate-mass nuclei which could be observable on the most metal-deficient stars. These signatures stem from the unique relative abundances for intermediate-mass elements, when produced by neutron-capture nucleosynthesis, compared with the abundances produced by normal stellar thermonuclear burning.

Although the uncertainties in the neutron-capture rates are large, we propose that baryon-number–inhomogeneous primordial nucleosynthesis could be characterized by a large elemental carbon abundance with a large ^{13}C/^{12}C ratio such that ^{13}C and ^{12}C have comparable abundances independent of the total baryon density as long as the fluctuations have significant amplitudes and a small volume fraction. Similar signatures could be found in a high ^{17}O/^{16}O ratio (particularly if the present fraction of the closure density contributed by baryons, Ω_b, is near unity), an enhanced ^{21}Ne/^{20}Mg ratio if the fluctuation amplitude is small, and an enhanced ^{25}Mg/^{24}Mg ratio together with an enhanced or depleted ^{26}Mg/^{24}Mg ratio depending upon Ω_b. For elemental ratios we propose that a C/N ratio similar to solar, and an overall high abundance of heavy nuclei, may indicate inhomogeneous nucleosynthesis. In this paper, stated values of Ω_b are based upon a present back-

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ground temperature of 2.7 K and a present Hubble constant of $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

II. THE CALCULATION

The starting point for this calculation is the big bang nucleosynthesis code of Wagoner (1973) with a number of nuclear reaction rates updated (e.g., Caughlan and Fowler 1988). We use three neutrino flavors and a neutron half-life of 10.3 minutes. Because of the unique history of the neutron-rich and proton-rich environments, it is necessary to include a number of new reaction rates not present in the original code.

a) Nuclear Reaction Network

The network used in this calculation is summarized in Figure 1. The major modification necessary for nuclei up to $Z = 12$ is the addition of the $^8\text{Li}(d, n)^9\text{Be}$ and $^8\text{Li}(n, \gamma)^9\text{Li}$ (Malaney and Fowler 1988) and $^7\text{Li}(^3\text{H}, n)^9\text{Be}$ and $^9\text{Be}(^3\text{H}, n)^{11}\text{B}$ (Boyd and Kajino 1989) reactions to the network which provides a leak from the *p–p* chain and allows for the production of heavy elements, e.g.,

$$^1\text{H}(n, \gamma)^2\text{H}(n, \gamma)^3\text{H}(d, n)^4\text{He}(^3\text{H}, \gamma)^7\text{Li}(n, \gamma)^8\text{Li} ,$$
$$^8\text{Li}(\alpha, n)^{11}\text{B}(n, \gamma)^{12}\text{B}(\beta\bar{\nu})^{12}\text{C}(n, \gamma)^{13}\text{C}(n, \gamma)^{14}\text{C} . \quad (1)$$

For elements heavier than ^{14}C we have found that it is necessary to include the many neutron-capture rates for unstable nuclei depicted in Figure 1. We have found that $^{14}\text{C}(n, \gamma)^{15}\text{C}$ and subsequent neutron captures and beta decays give the principal route to the production of heavy elements. This is in contrast to the results of Applegate, Hogan, and Scherrer (1988) and Malaney and Fowler (1988), where $^{14}\text{C}(\alpha, \gamma)^{18}\text{O}$ plays the major role in heavy-element production. This difference can be traced to the value for the $^{14}\text{C}(n, \gamma)^{15}\text{C}$ cross section used in those works compared with the present work.

There is only an upper limit to the measured thermal neutron-capture cross section of $\sigma_{\text{th}}(^{14}\text{C}) < 1$ μbarn (Ajzenberg-Selove 1981). A simple $E^{-1/2}$ extrapolation of this value to a typical neutron-capture energy of 30 keV would imply an upper limit of $\sigma_{30}(^{14}\text{C}) < 1$ nbarn, which would not compete well with the $^{14}\text{C}(\alpha, \gamma)^{18}\text{O}$ cross section.

We can understand this low thermal capture cross section for ^{14}C in the framework of the direct radiative capture model (Lane and Lynn 1960). The S-wave thermal neutron-capture rate for ^{14}C is dominated by an E2 transition to the $J^\pi = 5/2^+$ level of ^{15}C at 0.740 MeV. The M1 transition to the ground state is suppressed because the ground state represents a single neutron in the $2s_{1/2}$ level and therefore has poor spatial overlap with the entrance channel owing to a change in the radial quantum number between the entrance channel and the final state. We predict a neutron capture cross section at 30 keV based upon this channel of 0.1 nbarns, which is well below the observed upper limit. However, this argument neglects the contribution from other electromagnetic modes. In particular, the $l = 1$, E1 transition to the $1/2^+$ ground state increases with the square root of the incident kinetic energy (rather than the usual $E^{-1/2}$ dependence for the S-wave contribution), so that we derive a cross section of 0.1 mbarns at 30 keV. Thus, the neutron-capture rate on ^{14}C could exceed the alpha-capture

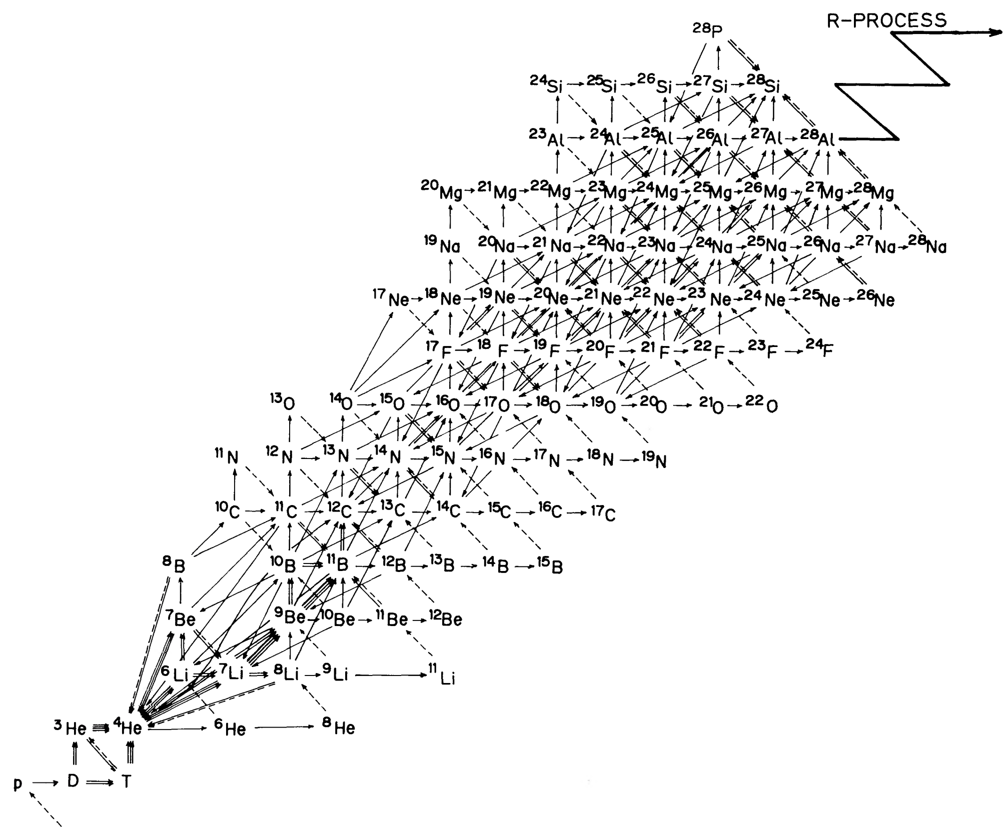

FIG. 1.—Nuclear reaction network used in the calculations. Solid arrows indicate nuclear reactions in the direction of positive Q-value; dashed arrows show beta decays.

rate at these energies as a path to heavy nuclei. Furthermore, contrary to the suggestion in Applegate, Hogan, and Scherrer (1988), we find that cycling due to the $^{17}O(n, \alpha)^{14}C$ reaction is not a significant hindrance to the neutron-capture flow through this region. It has also been pointed out (Wiescher, Görres, and Thielemann 1990) that the (γ, n) rate on ^{15}C may compete with the beta-decay rate at high temperature because of the low neutron binding energy for ^{15}C. Thus, proton captures may be more important than neutron captures on ^{14}C until late times in the big bang.

To obtain the neutron-capture rates of other nuclei, we have used several available sources. We use measured values at 30 keV (Bao and Kappeler 1987) whenever available, except for the $^{12}C(n, \gamma)^{13}C$ rate, for which the measured value is so uncertain (0.2 ± 0.4 mbarns) that an extrapolation of the measured thermal cross section is probably best. Unlike ^{14}C, the $l = 1$ contribution to the $^{12}C(n, \gamma)^{13}C$ cross section is unimportant. We thus obtain a value at 30 keV of $\sigma_{30} = 3.0$ μbarns (Mughabghab, Divadeenam, and Holden 1981). For other unmeasured nuclei we use a preliminary version of Hauser-Feshbach estimates from Thielemann (1989) or the approximate formulae of Woosley *et al.* (1975). For most of the light- to intermediate-mass nuclei of interest in this work, there should be sufficient level density in the compound nucleus ($\gtrsim 10$ MeV^{-1}) near the neutron separation energy that one expects the statistical model to be valid (Woosley *et al.* 1975). We note, however, that recent estimates of Thielemann and Wiescher (1990) suggest somewhat smaller cross sections than our estimates for nuclei from lithium to neon. The uncertainties in these estimated cross sections may introduce as much as a factor of 2 uncertainty in the calculated abundances but should not affect our qualitative conclusions.

In addition to the extension of the neutron-capture network to neutron-rich nuclei, we have also extended the charged-particle reaction network up to ^{28}P on the proton-rich side of stability. The charged-particle reaction rates are from recent compilations (e.g., Caughlan and Fowler 1988). The reason for this extension was to investigate the possibility of an rp-process environment (Wallace and Woosley 1981) developing in the proton-rich regions. We find that the most significant heavy-element production in the proton-rich regions is for the elements ^{12}C, ^{13}C, and ^{14}N, which are produced via the CNO or beta-limited CNO cycles:

$$2\,^4He(\alpha, \gamma)^{12}C(p, \gamma)^{13}N(\beta^+ \nu)^{13}C(p, \gamma)^{14}N(p, \gamma)^{15}O(\beta^+ \nu)$$

$$\text{or} \qquad\qquad ^{15}N(p, \alpha)^{12}C$$

$$^{13}N(p, \gamma)^{14}O(\beta^+ \nu)^{14}N(p, \gamma)\ .$$

Once this cycle is established, there is some slight breakout into a kind of rp-process dominated by a series of proton and alpha captures to produce the alpha-particle nuclei, ^{16}O, ^{20}Ne, ^{24}Mg, and ^{28}Si.

b) Neutron Diffusion

The other major modification to the big bang nucleosynthesis code is, of course, the diffusion of neutrons before and during primordial nucleosynthesis. In a number of papers (Malaney and Fowler 1988; Applegate, Hogan, and Scherrer 1988; Kajino, Mathews, and Fuller 1989; Mathews *et al.* 1989, 1990; Kurki-Suonio and Matzner 1989; Terasawa and Sato 1989) the importance of diffusion during nucleosynthesis has been discussed. The essential point is that, if the average separation between fluctuations is sufficiently short compared with the neutron diffusion length during primordial nucleosynthesis, then there will be a flow of neutrons from the neutron-rich zones into the proton-rich regions, where the neutrons are more quickly absorbed by nuclear reactions. On the other hand, if the separation between fluctuations is too large compared with the neutron diffusion length before nucleosynthesis, then not enough neutrons flow into the low-density zones to produce significant variations in the n/p ratio.

The best agreement with light-element abundances for a large value of Ω_b is obtained for separation distances just comparable to the neutron diffusion length during nucleosynthesis (Mathews *et al.* 1990). In this case there is enough diffusion before nucleosynthesis to produce the neutron-rich zones; however, there is not so much diffusion after the onset of nucleosynthesis that neutrons are significantly depleted from the low-density zones. We note that baryon-number fluctuation shapes and separations which lead to satisfactory light-element nucleosynthesis (Mathews *et al.* 1990) share some common characteristics: the fluctuation amplitudes, R, are large compared with unity; the volume fraction of the high-density zones, f_v, is small; and, as previously remarked, the mean separation between fluctuation centers tends to be on the order of the neutron diffusion length during the nucleosynthesis epoch. Note that the fluctuation characteristics are modified between the time of formation (e.g., in a possible cosmic quark-hadron phase transition) and the time of nucleosynthesis by neutron diffusion. Thus the fluctuation density contrast at the time of intermediate-mass nucleosynthesis, R, is only indirectly related to the value at the time of formation of the fluctuation.

If the neutron diffusion takes place just before nucleosynthesis, as implied by models which best fit the light-element abundance yields (Mathews *et al.* 1989, 1990), then the baryon-density enhancement, Ω_h/Ω_b, and neutron mass fraction, X_n^h, in the high-density regions can be approximated (Fuller, Mathews, and Alcock 1988) by

$$\frac{\Omega_h}{\Omega_b} = X_n = \frac{R(1 - X_n)}{Rf_v + 1 - f_v}\,,$$

$$X_n^h = \frac{X_n}{\Omega_h}\,. \tag{1}$$

Similarly, in the low-density regions we write

$$\frac{\Omega_l}{\Omega_b} = X_n + \frac{1 - X_n}{Rf_v + 1 - f_v}\,,$$

$$X_n^l = \frac{X_n}{\Omega_l}\,, \tag{2}$$

where $X_n(\sim 0.12)$ is the neutron mass fraction just before neutron diffusion and nucleosynthesis.

We neglect neutron diffusion during nucleosynthesis. This is justified for the low-density neutron-rich regions where the bulk of neutron-capture nucleosynthesis proceeds, since these regions have a large spatial length scale [$\approx (1 - f_v^{1/3})l$, where l is the distance between fluctuations and $f_v \ll 1$], so that neutron density gradients are small and the flow of neutrons is confined to the boundary between high- and low-density regions (Mathews *et al.* 1990). For the high-density regions however, the spatial extent is small ($\approx f_v^{1/3} l$), and hydrodynamic effects may lead to enhanced back-diffusion of neutrons (Alcock *et al.* 1990). Nevertheless, the diffusion of neutrons back into the high-density regions is inhibited by the large baryon density and hence short mean free path (Mathews *et al.* 1990). in the high-density regions.

These considerations and the fact that the time scale for the nucleosynthesis of the bulk of the intermediate-mass elements is shorter than the time scale over which significant diffusions and hydrodynamic effects are important justify the use of single-zone models for the high- and low-density regions in the present work. The models we use approximately reproduce the neutron density or proton density as a function of time obtained previously in models for which the diffusion was solved simultaneously with a nuclear reaction network up to $A = 16$ (Mathews *et al.* 1989, 1990) with up to 32 zones. There is good agreement between the results obtained using this one-zone model and those obtained from the multizone models for most of the light elements (except for the special case of ^{7}Li, which is destroyed at the boundary of the high- and low-density zones; Applegate, Hogan, and Scherrer 1988; Malaney and Fowler 1988; Mathews *et al.* 1990). Nevertheless, we point out that the present results can only be considered upper limits to the production of intermediate-mass elements in the inhomogeneous big bang, owing to the neglect of diffusion after the onset of primordial nucleosynthesis (cf. Terasawa and Sato 1990).

III. RESULTS

a) Characterization of the Models

As discussed above, most of the significant heavy-element production will occur in the most neutron-rich regions. Furthermore, for big bang models which best satisfy the light-element abundance constraints (Mathews *et al.* 1990) these neutron-rich zones are not much affected by baryon diffusion after the onset of the epoch of primordial nucleosynthesis because these zones are separated from the high-density zones. Therefore, we can parameterize the heavy-element nucleosynthesis in these regions simply by specifying the local relative baryon density in the neutron-rich and proton-rich region and the neutron mass fraction, X_n, in these regions just before the beginning of nucleosynthesis (at $T \cong 1.3 \times 10^9$ K) but after neutron diffusion equilibrium. The total primordial mass fraction of these heavy elements for any inhomogeneous big bang model will then be given by the product of these computed mass fractions times the volume fraction, f_v, occupied by such zones times the ratio of the local baryon density to the average baryon density. Thus, the results presented here immediately apply to a broad range of inhomogeneous big bang models. As shown above, for small f_v, the local baryon density and neutron mass fraction in the neutron-rich regions can be determined for a large range of models simply by specifying Ω_b and the product of the fluctuation amplitude times the volume fraction, Rf_v. Thus, we characterize the models with these two parameters.

For the purposes of illustration we consider values for Rf_v of 10 ($R = 20, f_v = 0.5$) and $Rf_v = 100$ ($R = 5 \times 10^4, f_v = 0.002$). This corresponds to $X_n^l = 0.60$ and 0.94, and local values in the low-density neutron-rich zone of $\Omega_l/\Omega_b = 0.21$ and 0.13. For the high-density proton-rich region these same conditions yield $\Omega_h/\Omega_b = 1.9$ and 570 with $X_n^h = 0.067$ and 2×10^{-4}. For Ω_b we consider values of 1.0 and 0.1. These parameter sets are representative of conditions which could satisfy most of the light-element abundance constraints (Fuller, Mathews, and Alcock 1988; Mathews *et al.* 1989, 1990). They are therefore indicative of the kind of observational signatures which could emerge. These results will be compared with results from standard big bang nucleosynthesis with $\Omega_b = 1.0$ and 0.1.

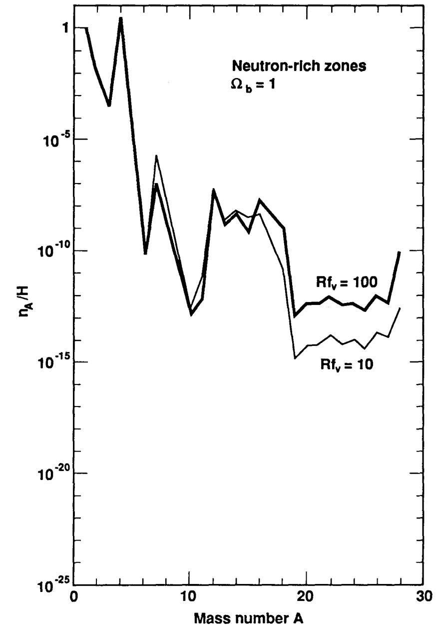

FIG. 2.—Calculated abundances as a function of mass number for nuclei produced in the neutron-rich zones in $\Omega_b = 1.0$ models. For comparison, results are shown for a large-amplitude fluctuation, $Rf_v = 100$ (*heavy solid line*) and a small fluctuation amplitude, $Rf_v = 10$ (*thin solid line*).

b) Neutron-rich Nucleosynthesis

Figure 2 shows examples of calculated abundances in the neutron-rich regions as a function of atomic mass for $Rf_v =$ 100 and 10 and $\Omega_b = 1.0$. Figure 3 shows the same for $\Omega_b = 0.1$.

Reasonable variations of the fluctuation parameter, Rf_v,

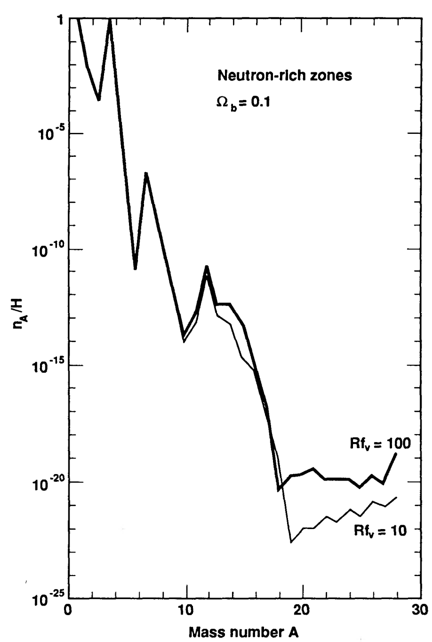

FIG. 3.—Same as Fig. 2, but with $\Omega_b = 0.1$

serve only to displace the curves in Figures 2 and 3 slightly up or down without changing the qualitative results. Therefore, the most important parameter is Ω_b.

The main neutron-capture flow responsible for the heavy-element abundances in Figure 2 passes through nuclei with beta half-lives ~2 minutes, i.e., ^{15}C, ^{16}N, ^{19}O, ^{20}F, ^{23}Ne, ^{25}Na, and ^{27}Mg. The drop in the abundances for $A > 18$ is due to the small neutron-capture cross section for ^{18}O. For $A \geq 19$ the abundances reach a plateau of 10^{-12} to 10^{-14} for $\Omega_b = 1$ and 10^{-21} to 10^{-20} for $\Omega_b = 0.1$.

The heaviest isobar in the network ($A = 28$) contains all of the flow which would have led to yet heavier nuclei. From the abundance of this last point we can therefore estimate limits on the production of heavy (r-process) nuclei in such inhomogeneous big bang models. From Figures 2 and 3 we estimate that the production of seed material for an r-process probably does not exceed a mass fraction $X_{\text{seed}} \sim 10^{-9}$ for any value of Ω_b. In principle, the r-process mass fractions, X_r, could exceed this value as a result of fission recycling (Applegate, Hogan, and Scherrer 1988; Malaney and Fowler 1988),

$$X_r = X_{\text{seed}} \times 2^n , \quad (3)$$

where n is the number of fission cycles (Mathews and Ward 1985). Along the neutron-capture flow in our network the beta-decay lifetimes are ~1 minute for nuclei with capture cross sections ~1–10 mbarns. Assuming an average capture cross section of ~100 mbarns for heavy nuclei, the corresponding beta lifetime along the path will be ~1–10 s. This implies a total cycle time from iron to actinide nuclei of ~100–1000 s. This is a long time scale for a classical r-process (Mathews and Ward 1985) and is a result of the somewhat lower proper neutron density ($\lesssim 10^{17}$ cm^{-3}) in our models compared with a classical r-process.

Figure 4 shows an illustration of the proper neutron density as a function of time in the neutron-rich region. At the onset of nucleosynthesis, $t \sim 100$ s, the neutron density is as high as 10^{19} cm^{-3}. However, by the time nucleosynthesis ends at $t \sim 1000$ s, the neutron density has dropped by as much as three orders of magnitude. Because of this lower neutron density, the flow path moves much closer to stability than for a classical r-process (Mathews and Ward 1985). This is the reason that our estimated cycle time is much longer than that

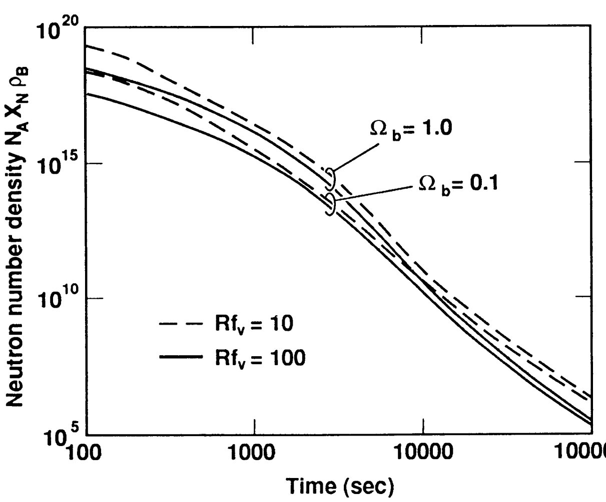

FIG. 4.—Proper neutron density as a function of time for the neutron-rich region in the various models.

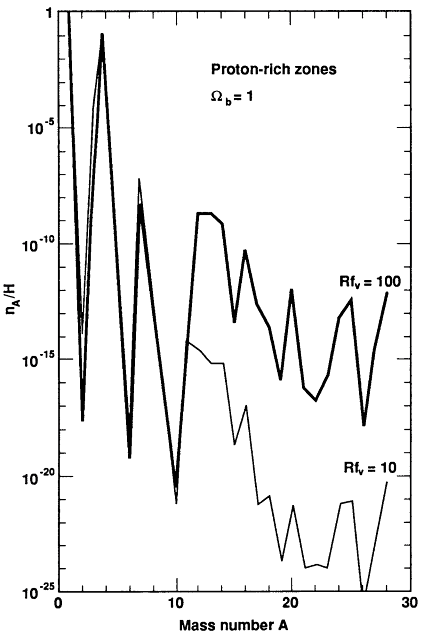

FIG. 5.—Nucleosynthesis yields in the proton-rich region for $\Omega_b = 1.0$ models.

in Applegate, Hogan, and Scherrer (1988). We thus estimate that there are not likely to be more than a few fission cycles during a primordial r-process. This is important, since halo stars are observed (Gilroy *et al.* 1988) with r-process elemental mass fractions as low as 10^{-10}, which is close to the estimated maximum r-process production. Thus, it may be that the heavy-element abundances are an observable signature in inhomogeneous big bang models. We note that our conclusions regarding the lower neutron density and lower heavy-element abundances in a primordial r-process have recently been confirmed (Thielemann *et al.* 1990) in a calculation which extends the nucleosynthesis network up to actinide nuclei. They find that at best there are few fission cycles, the heavy-element mass fraction is $\ll 10^{-9}$ and the final abundance pattern more closely resembles an s-process distribution than a r-process.

c) Proton-rich Nucleosynthesis

Figures 5 and 6 show nucleosynthetic yields in the proton-rich region as a function of mass number for our $\Omega_b = 1.0$ and 0.1 models, respectively. The heavy-element abundances depend much more strongly upon the fluctuation parameter, Rf_v, than in the neutron-rich regions. The reason is that large values of R can lead to very high baryon densities in the proton-rich regions. A high baryon density allows the buildup of heavy elements by proton and alpha-particle reactions before the temperature drops too low for the reactions to overcome the Coulomb barrier (unlike neutrons, for which reactions can proceed over a much longer time scale). Thus, the largest heavy-element yields in the proton-rich region are produced in the large Rf_v and $\Omega_b = 1.0$ models. The other models are not much different from the standard big bang, except for an excess of nuclei with $A \gtrsim 20$ at an abundance of 10^{-18} to 10^{-20} relative to hydrogen. In the $\Omega_b = 1.0$, $Rf_v = 100$ model the breakout from the CNO cycle is primarily from the ^{12}C(α, γ)^{16}O reaction, from which a series of alpha-particle and proton-capture reactions (reminiscent of oxygen burning in

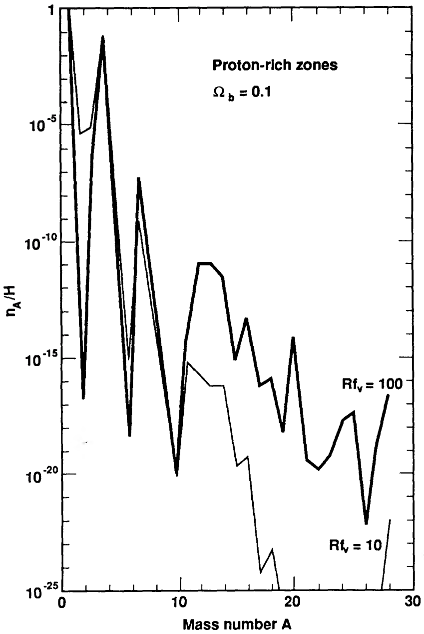

FIG. 6.—Same as Fig. 5, but for $\Omega_b = 0.1$ models

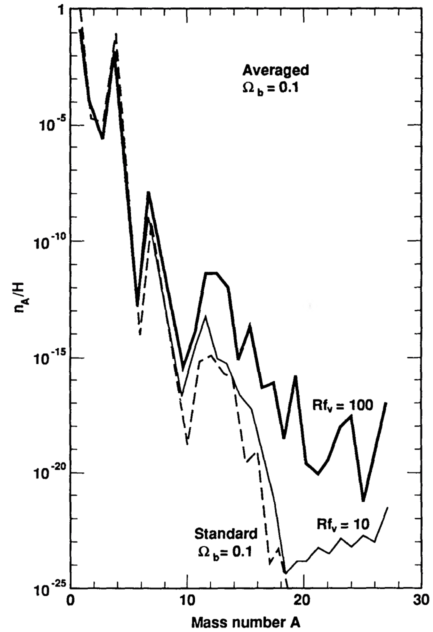

FIG. 8.—Averaged nucleosynthetic yields from the $\Omega_b = 0.1$ baryon-inhomogeneous models compared with the standard homogeneous big bang.

presupernova massive stars) lead to a preponderance of ^{16}O, ^{20}Ne, ^{24}Mg, and ^{28}Si at an abundance of 10^{-13} to 10^{-10} relative to hydrogen. The production of other intermediate-mass elements is for the most part insignificant relative to their production in the neutron-rich region.

d) Observational Signatures

Figures 7 and 8 show abundances averaged over the proton-rich and neutron-rich regions, respectively, for the $\Omega_b = 1.0$ and 0.1 models, respectively. For the models with high Rf_v there are contributions to intermediate-mass nuclei from both proton-rich and neutron-rich regions, whereas for the models

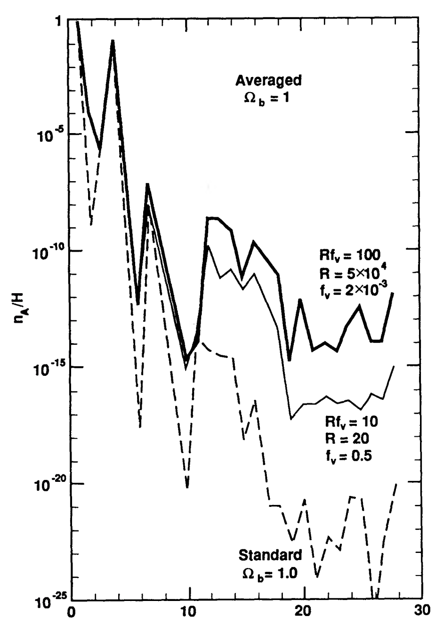

FIG. 7.—Averaged nucleosynthetic yields from the $\Omega_b = 1.0$ baryon-inhomogeneous models compared with the standard big bang (*dashed line*).

with low Rf_v the neutron-rich regions dominate as a nucleosynthesis site. There is also a strong dependence on Ω_b independent of Rf_v. These two possibilities may allow for observational signatures which can be used for an identification of both the fluctuation amplitude and the average baryon density from an inhomogeneous big bang.

As a clue to how such an analysis might proceed, in Table 1 we summarize the calculated isotopic abundance ratios relative to solar from these models. Several possibilities emerge, although at a very low and difficult-to-measure abundance. For one, the ^{13}C/^{12}C ratio approaches unity in the large fluctuation models or the homogeneous big bang, although at a lower abundance. This is independent of Ω_b and is due to the effects of neutron capture on ^{12}C. The ^{15}N/^{14}N isotopic ratio, however, is only slightly enhanced relative to solar, so that one important observational signature could be CN molecular lines with a large contribution from ^{13}C.

Similar possible isotopic signatures are the ^{17}O/^{16}O ratio (which is enhanced for large-Ω_b inhomogeneous models independent of the fluctuation shape), the ^{21}Ne/^{20}Ne ratio (which is particularly enhanced in the low Rf_v models as a result of the effects of neutron capture on ^{20}Ne), and the ^{25}Mg/^{24}Mg ratio, which is in excess of solar to such an extent that elemental magnesium becomes 85% ^{25}Mg. As in the case of ^{13}C/^{12}C, this enhancement is largely independent of the value of Ω_b in the models.

It would be easier (although perhaps not as convincing) to search for signatures of inhomogeneous nucleosynthesis in elemental abundances. In Figures 9 and 10 we show elemental abundances compared with the data from Bessel and Norris (1984) for low-metallicity Population II stars. It is perhaps encouraging that the $\Omega_b = 1.0$, $Rf_v = 100$ model is not too far below the observations. Thus, by making observations of yet more metal-poor objects, it may be possible to confirm or deny this important cosmological possibility. As far as an elemental signature of baryon-number inhomogeneities is concerned, we point out that in the $\Omega_b = 1$ models the C/N ratio approaches

TABLE 1

LOGARITHMIC ISOTOPIC RATIOS[a]

RATIO[a]	$\Omega_b = 1.0$			$\Omega_b = 0.1$		
	$Rf_v = 100$	$Rf_v = 10$	Standard	$Rf_v = 100$	$Rf_v = 10$	Standard
$[^{13}C/^{12}C]$	*1.88*[b]	0.34	1.72	*2.00*	0.06	1.28
$[^{15}N/^{14}N]$	0.34	1.52	−1.10	−0.82	0.99	−1.12
$[^{17}O/^{16}O]$	*2.76*	*2.25*	−1.08	0.71	1.36	−1.54
$[^{18}O/^{16}O]$	1.35	0.31	−1.83	0.25	−1.32	−1.44
$[^{21}Ne/^{20}Ne]$	0.34	*2.64*	−0.75	−1.34	*2.65*	...
$[^{22}Ne/^{20}Ne]$	−0.89	1.50	−0.43	−3.26	1.68	...
$[^{25}Mg/^{24}Mg]$	*1.69*	0.53	0.86	*1.40*	0.47	...
$[^{26}Mg/^{24}Mg]$	0.09	1.19	−4.58	−2.52	1.00	...

[a] Ratios are relative to solar (Anders and Grevesse 1989), from various baryon-number–inhomogeneous big bang models and the standard homogeneous big bang.

[b] Italicized quantities identify those measurements that should be most valuable for identifying the inhomogeneous big bang models (see text).

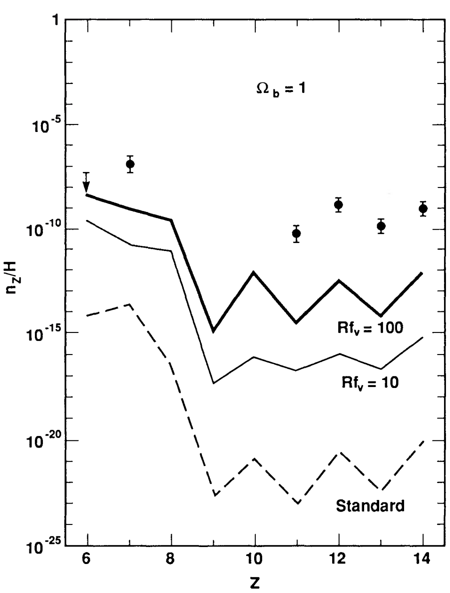

FIG. 9.—Averaged elemental abundances for inhomogeneous models with $\Omega_b = 1.0$ compared with data from Bessel and Norris (1984) (*filled circles*).

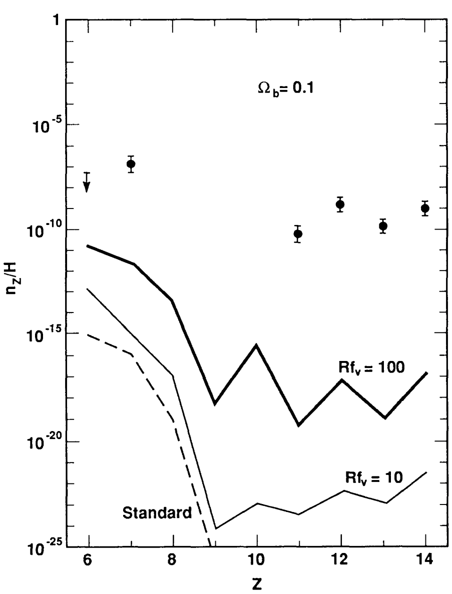

FIG. 10.—Same as Fig. 9, but with $\Omega_b = 0.1$

the solar ratio for large Rf_v, whereas the models with small Rf_v could have enhancements of C/N relative to solar while the standard big bang has a diminished C/N ratio. This can be traced to the production of ^{14}N by the CNO cycle in the models with large baryon density. Thus observation of the C/N ratio could be useful.

IV. SUMMARY AND CONCLUSION

We have explored the consequences of nucleosynthesis for intermediate-mass elements in baryon-number–inhomogeneous cosmologies. We find that there is no contradiction to observed Population II abundances for intermediate-mass elements. On the contrary, there may be several opportunities for a determination of the validity of such models. Several possible abundance determinations, including the $^{13}C/^{12}C$, $^{17}O/^{16}O$, $^{21}Ne/^{20}Ne$, and $^{25}Mg/^{24}Mg$ isotopic ratios, as well as the C/N elemental ratio, and the existence of a floor to the observed metallicity, are proposed as possible signatures of baryon-number inhomogeneities in the early universe.

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