Inhomogeneous Big Bang Nucleosynthesis with Late–Decaying Massive Particles

J. López–Suárez¹ and R. Canal¹.²

Received ______________; accepted ______________

Running title: Big Bang Nucleosynthesis

¹Department of Astronomy, University of Barcelona, Martí i Franqués 1, E–08028 Barcelona, Spain. E–mail: jlopez@mizar.am.ub.es, ramon@mizar.am.ub.es

²Institut d’Estudis Espacials de Catalunya/UB, Edif. Nexus–104, Gran Capità 2–4, 08034 Barcelona, Spain
ABSTRACT

We investigate the possibility of accounting for the currently inferred primordial abundances of D, $^3$He, $^4$He, and $^7$Li by big bang nucleosynthesis in the presence of baryon density inhomogeneities plus the effects of late–decaying massive particles (X), and we explore the allowed range of baryonic fraction of the closure density $\Omega_b$ in such context. We find that, depending on the parameters of this composite model (characteristic size and density contrast of the inhomogeneities; mass–density, lifetime, and effective baryon number in the decay of the X particles), values as high as $\Omega_b h^2_{50} \simeq 0.25 - 0.35$ could be compatible with the primordial abundances of the light nuclides. We include diffusion of neutrons and protons at all stages, and we consider the contribution of the X particles to the energy density, the entropy production by their decay, the possibility that the X–products could photodissociate the light nuclei produced during the previous stages of nucleosynthesis, and also the possibility that the decay products of the X–particles would include a substantial fraction of hadrons. Specific predictions for the primordial abundance of Be are made.

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

Standard homogeneous big bang nucleosynthesis could have produced the observationally inferred primordial abundances of D, $^3$He, $^4$He, and $^7$Li, provided that the baryon fraction of the cosmic closure density $\Omega_b$ would lie in the range:

$$0.04 \lesssim \Omega_b h_{50}^2 \lesssim 0.08$$

(1)

where $h_{50}$ is the Hubble constant in units of 50 km s$^{-1}$ Mpc$^{-1}$ (Walker et al. 1991; Copi, Schramm, & Turner 1995). For the long–time most favored cosmological model, a flat Universe with $\Omega_M = 1$ and $\Omega_\Lambda = 0$ (those being, respectively, the fractional contributions of matter and vacuum energy densities to the closure density), the upper bound to $\Omega_b$ would mean that most matter in the Universe should be in nonbaryonic form. Given the far–reaching implications of the dominance of nonbaryonic dark matter, possible alternatives to homogeneous big bang nucleosynthesis have been explored, especially during the last 15 years or so.

The suggestion that the quark–hadron phase transition might be first–order and generate baryon inhomogeneities (Witten 1984) led to the calculation of the possible effects on primordial nucleosynthesis (Applegate & Hogan 1985; Applegate, Hogan, & Scherrer 1987; Malaney & Fowler 1988). The goal was to see whether inhomogeneous big bang nucleosynthesis with $\Omega_b = 1$ might account for the primordial light–element abundances. Besides a first–order quark–hadron phase transition, other mechanisms might also generate baryon inhomogeneities. Much of the work in this line is reviewed by Malaney & Mathews (1993). However, the recent studies, treating accurately the coupling between baryon diffusion and nucleosynthesis, show that the upper limit on $\Omega_b$ set by the light–element abundances does not significantly differ from that obtained for homogeneous big bang
nucleosynthesis (Mathews, Schramm, & Meyer 1993; Thomas et al. 1994). This last conclusion, though, has very recently been challenged by Orito et al. (1997), who explore the dependence of primordial nucleosynthesis on the geometry of baryon inhomogeneities and find that cylindrical geometry might allow to satisfy the observational constraints with baryon fractions as high as $\Omega_b h_{50}^2 \lesssim 0.2$.

A different approach has been to explore the possible modifications of the yields from homogeneous big bang nucleosynthesis by the effects of the decay of unstable massive particles ($M \gtrsim \text{few GeV}$), produced at earlier stages in the evolution of the Universe and with half–lives longer than the standard nucleosynthesis epoch ($\tau_x \gtrsim 10^4 \text{ s}$) (Audouze, Lindley, & Silk 1985; Domínguez–Tenreiro 1987; Yepes & Domínguez–Tenreiro 1988; Dimopoulos et al. 1988). Gravitinos produced during reheating at the end of inflation are a possible example of such particles. In Dimopoulos et al. (1988), the emphasis is put on the resulting hadron cascade. The main problem encountered in this model is the predicted overproduction of $^6\text{Li}$: $^6\text{Li}/^7\text{Li} \gg 1$, whereas observations show $^6\text{Li}/^7\text{Li} \lesssim 0.1$.

Although they have only been considered separately, baryon inhomogeneities and the presence of unstable massive particles decaying when the Universe has already cooled down below $T_9 \simeq 0.4$ are by no means mutually exclusive. Here we explore their combined effects on the primordial abundances of the light elements. The parameter space now has, of course, a dimension which is the sum of those for the two separate cases: characteristic size and density contrast of the inhomogeneities, mass–density, lifetime, and mode of decay of the massive particles. We find that there are regions in such extended parameter space where values of $\Omega_b$ as high as $\Omega_b h_{50}^2 \simeq 0.35$ would still be compatible with the primordial abundances of the light nuclides inferred from observations. Such values of $\Omega_b$ are of the same order as the low values for $\Omega_M$ currently derived from a variety of sources, including high–redshift supernova searches (Perlmutter et al. 1998; Garnavich et al. 1998).
results thus suggest again the possibility that all the matter in the Universe could be baryonic.

On the other hand, recent determinations of the D abundance in high–redshift QSO absorbers, when confronted with the currently inferred primordial $^4$He abundance, might be in conflict with the predictions of standard, homogeneous big bang nucleosynthesis for $N_\nu = 3$ (Steigman 1998): the “low” high–redshift D abundances (which appear more reliable) would indicate too high a value of $\Omega_b$ to be compatible with that corresponding to the $^4$He abundance. Since it is hard to tell whether this conflict points to new physics or just to systematic errors in the derivation of abundances, Steigman, Hata, & Felten (1998) have discarded the constraint on $\Omega_b$ from standard big bang nucleosynthesis and turned to other observational constraints to determine the key cosmological parameters. The results from our composite model, by showing how minor deviations from the standard hypotheses can produce agreement with the primordial abundances inferred from observations, support that attitude. Besides, as we will see, the combined effects of inhomogeneities plus late–decaying particles might solve the conflict between D and $^4$He abundances.

2. Model, Results, and Discussion

In the present model, nucleosynthesis first takes place in a Universe with baryon inhomogeneities. Later, when the temperatures are low enough for the chemical abundances to be frozen, unstable massive particles start to decay producing both hadronic and electromagnetic showers which alter the abundances of the light elements resulting from the previous stage.

For the inhomogeneities, we consider a simple model consisting of two types of zones, one with high density and the other with low density, characterized by their respective
volume fractions $f_v$ and $1 - f_v$, and by the density contrast $R$ between the two zones (see Thomas et al. 1993). The inhomogeneities, produced at some earlier stage, lead to differential diffusion of protons and neutrons when the temperature, in the expanding Universe, drops below $T \simeq 1$ MeV and protons and neutrons are no longer in equilibrium (Applegate & Hogan 1985). Then, due to the much longer mean free path of the neutrons, the initial baryon inhomogeneities transform into variations of the local neutron/proton ratio (Applegate, Hogan, & Scherrer 1987, 1988; Rauscher et al. 1994). When nucleosynthesis starts at $T_9 \simeq 1$, neutrons are already uniformly distributed whereas the protons retain the spatial distribution they had at weak decoupling. Nucleosynthesis thus takes place in two different types of zones: the proton–rich and the neutron–rich ones. Since almost all neutrons end up into $^4$He, with the rapid growth of the abundance of this nuclide protons become exhausted in the neutron–rich zones and the same occurs with neutrons in the proton–rich zones. A density contrast thus appears again and neutrons start to diffuse back from the neutron–rich zones into the proton–rich ones. We have coupled neutron diffusion with the nuclear reaction network as in Rauscher et al. (1994).

On the other hand, we have the X–particles, with masses $m_x$ and half–lives $\tau_x$. The particles are massive ($m_x > 10$ GeV) and we consider only half–lives in the interval $10^4$ s \leq \tau_x \leq 10^7$ s. The former means that they are nonrelativistic well before the start of nucleosynthesis. The lower limit to the half–life implies that the thermonuclear reaction rates have dropped to zero before the X–particles start to disintegrate, while the upper limit ensures that their decays leave no imprint on the cosmic background radiation. Prior to decaying, the X–particles just give a contribution $\rho_x$ to the matter–energy density. We define $r$ as the number ratio of the X–particles to photons at some fiducial temperature $T_0$. Here we follow the history of cosmic expansion starting at $T_0 = 10^{12}$ K. The product:
\[
\frac{dY_i}{dt} = \pm \delta_{in} \kappa Y_n + \frac{\eta_0 m_x}{\tau_x} \exp(-t/\tau_x) \left[ \xi_i r_B^* B - Y_i Y_p \int_{E_{\text{max}}}^{E_{\text{max}}} \frac{\epsilon_\gamma(E) \sigma_{\gamma\gamma}(E)}{\sigma_C(E)} dE \right] + \left( \frac{dY_i}{dt} \right)_{\text{std}} (3)
\]

where the + sign corresponds to the proton–rich zone, the – sign to the neutron–rich one, \( \kappa \) is the diffusion rate of neutrons, \( \eta_0 \) is the initial \( n_b/n_\gamma \) ratio, \( r_B^* \) is the effective baryonic branching ratio of the X–decays, \( \epsilon_\gamma(E) \) is the photon spectrum produced by disintegration of the X–particles, \( \sigma_{\gamma\gamma}(E) \) is the photodissociation cross–section, and \( \sigma_C(E) \) is the Coulomb scattering cross–section. The integrals extend from the photodissociation
threshold energy $Q_i$ to $E_{\text{max}} = m_e^2/(25T)$ (which thus increases with time). Subscripts $n$ and $p$ refer to neutrons and protons, respectively, and the subscript $\text{std}$ indicates the standard contribution of thermonuclear reactions to $dY_i/dt$. In order to deal with diffusion in the way indicated in (3), the nuclear abundances $Y_i \equiv N_i/N_b$ are taken relative to the total number of baryons in the given volume before neutron diffusion sets in, as in Rauscher et al. (1994). The neutron diffusion rate is given by:

$$\kappa = \frac{4.2 \times 10^4}{(d/a)} T_9^{5/4} (1 + 0.716T_9)^{1/2} \text{s}^{-1}$$

(4)

where $d/a$ (in cm MeV) is the comoving length scale of the inhomogeneities (Applegate, Hogan, & Scherrer 1988). The effective baryon branching ratio $r_B^*$ in (3) is another parameter of the model. It takes into account the dependence of the number of baryons produced by disintegration of the X–particles on their mass $m_x$ together with the dependence of the yields $\xi_i$ on the kinetic energies of the primary shower baryons:

$$r_B^* = \left(\frac{\nu_B}{5}\right) r_B F$$

(5)

where $r_B$ is the true baryonic branching ratio, and $F$ incorporates the dependence of the yields $\xi_i$ on the kinetic energy of the primary shower baryons (our "standard" $\xi_i$ have been calculated for $m_x = 1 \text{ TeV}$, $\nu_B = 5$, and $E_{\text{kin}} = 5 \text{ GeV}$). The photons produced by the decay of the X–particles have a spectrum:

$$\epsilon_\gamma(E) = \left(\frac{m_x}{2E_{\text{max}}^{1/2}}\right) E^{-3/2}$$

(6)

Our model, therefore, has five extra free parameters in addition to $\eta_0$: the volume fraction $f_v$ and the density contrast $R$ characterizing the inhomogeneities (but we also vary the comoving length scale $d/a$ governing neutron diffusion), the mass $m_x$ (in fact the
product \( rm_x \) and the half–life \( \tau_x \) of the X–particles, and the effective baryon ratio \( r_B^* \) in the X–particle decays. We thus solve the equations (5) for different combinations of those parameters, searching for the regions in the parameter space where the predicted primordial abundances of the light nuclides are compatible with those inferred from observations. The nuclear reaction network consists of 161 thermonuclear reactions, plus 20 reactions involved in the hadron cascades, plus 15 photodisintegration reactions. In following the expansion of the Universe we take into account the contribution of the X–particles to the total energy density and the entropy change due to their disintegration (assuming that the X–decay products thermalize on a time scale much shorter than the expansion time scale). The cross–section sources and a more detailed description of the model will be given elsewhere (see also López–Suárez 1997).

The set of primordial abundances to be fitted is the following:

\[
1.1 \times 10^{-5} \leq \left( \frac{D}{H} \right)_p \leq 2.5 \times 10^{-4} \tag{7a}
\]

\[
3.3 \times 10^{-5} \leq \left( \frac{D + ^3He}{H} \right)_p \leq 2.5 \times 10^{-4} \tag{7b}
\]

\[
0.21 \leq X(^4He)_p \leq 0.24 \tag{7c}
\]

\[
1.1 \times 10^{-10} \leq \left( \frac{^7Li}{H} \right)_p \leq 2.6 \times 10^{-9} \tag{7d}
\]

\[
\left( \frac{^6Li}{^7Li} \right)_p < 1 \tag{7e}
\]
The limits in (7a–e) are adopted, respectively, from McCullough (1992), Geiss & Reeves (1972), Pagel & Kazlaukas (1992), Krauss & Kernan (1994), and Smith, Lambert, & Nissen (1996). In (7e) we have adopted a conservative upper limit, taking account of the possibility that any primordial $^6$Li might have been partially destroyed ($^7$Li remaining almost intact) in metal–poor halo stars.

We have varied the volume fraction within the interval $0.01 \leq f_v \leq 0.28$, and the density contrast within $50 \leq R \leq 5000$. For the comoving length scale $d/a$, we have tried the cases without diffusion and with $10^{5.5} \text{ cm MeV} \leq d/a \leq 10^{7.5} \text{ cm MeV}$. For the parameters related to the X–particles, $10^{-5} \text{ GeV} \leq rm_x \leq 10^3 \text{ GeV}$, $1.5 \times 10^{-12} \leq r_B^* \leq 1.5 \times 10^{-9}$, and $10^4 s \leq \tau_x \leq 10^7 s$.

As an example of the results, in Figure 1 we show the dependence of the final D abundance on $\tau_x$, for three different values of $f_v$ and fixed values of $R$, $d/a$, $r_B^*$, $rm_x$, and $\eta_f$ (the final value of the baryon to photon ratio). We see that for $5 \times 10^5 s \lesssim \tau_x \lesssim 6 \times 10^5 s$ the resulting abundances fall within the range allowed by observations. In Figure 2 we show the dependence on $\tau_x$ of the final abundances of D, $^3$He, $^4$He, $^6$Li, $^7$Li, and $^9$Be, for fixed value of $f_v$ and the same values of the other parameters as in Figure 1. The two vertical dashed lines mark the interval of values of $\tau_x$ compatible with all the observationally inferred abundances of the light nuclides.

In summary, we obtain results which are compatible with the observations for little diffusion ($d/a = 10^{7.5} \text{ cm MeV}$), small abundances of the X–particles ($rm_x \sim 10^{-5} \text{ GeV}$), and modest numbers and energies of the shower baryons ($1.5 \times 10^{-12} \leq r_B^* \leq 1.5 \times 10^{-11}$). The density contrast between the two model zones must be $500 \leq R \leq 5000$, and the volume fraction $0.144 \leq f_v \leq 0.192$. The half–lives of the X–particles are $6.19 \times 10^5 s \leq \tau_x \leq 7.43 \times 10^5 s$, as illustrated in Figures 1 and 2. In that region of the parameter space $18 \leq \eta_{10} \leq 22$ ($\eta_{10}$ being here, as usual, $\eta$ in units of $10^{-10}$). That
corresponds to a baryon fraction:

\[ 0.25 \leq \Omega_b h^2_{50} \leq 0.35 \] (8)

in strong contrast with (1). A testable prediction of the present model is the production of an appreciable amount of $^9$Be:

\[ \left( \frac{^9 Be}{H} \right)_p \sim 10^{-13} \] (9)

The production of $^9$Be is characteristic of inhomogeneous big bang models (Malaney & Fowler 1989; Jedamzik et al. 1994; Orito et al. 1997). The current observational upper limit to the Be abundance (Duncan et al. 1997; García López et al. 1998) is of the same order as the values found here. There is, however, the problem that $B/Be \sim 10$ almost down to $[Fe/H] = -3$, and since our model predicts $B/Be < 1$, agreement would require a drop in the ratio taking place below some still smaller metallicity.

3. Conclusions

We have shown, by means of a simple model, that the combined effects on big bang nucleosynthesis of baryon inhomogeneities plus the decay of unstable, relatively long–lived massive particles, giving rise to both electromagnetic and hadron cascades, might be to allow agreement with the primordial light–element abundances inferred from observations for values of $\Omega_b$ much higher that those allowed by standard, homogeneous nucleosynthesis. The upper limit might be as high as $\Omega_b h^2_{50} \approx 0.35$. The values obtained here are of the same order as the low $\Omega_M$ values now being derived from a variety of sources and, therefore, they pose in new terms the question of whether all matter in the Universe could be baryonic. A
testable prediction of the model is the production of a $^9\text{Be}$ abundance that is of the order of current observational upper limits.

On the other hand, in the parameter region of our model where there is agreement between predicted and observationally inferred primordial light–element abundances, given values of $\Omega_b$ (or, equivalently, $\eta_{10}$) always predict “low” D abundances (in the sense of the high–redshift abundances referred to in the Introduction), thus potentially eliminating the conflict with the $^4\text{He}$ abundance pointed out by Steigman (1998).

The model presented here deals with inhomogeneities in a very simplified way. A further step will be to examine the effects of the geometry of the density fluctuations on the outcome. Orito et al. (1997) have already shown that cylindrical shell geometry alone (without the extra effects of late–decaying particles) might allow $\Omega_b \lesssim 0.2$ (but for density contrasts $R \sim 10^6$, much higher than those considered here). Another extension of the model will be to consider particles with shorter half–lives, decaying at the time when thermonuclear reactions are still taking place.
REFERENCES

Applegate, J.H., & Hogan, C.J. 1985, Phys. Rev. D, 30, 3037

Applegate, J.H., Hogan, C.J., & Scherrer, R.J. 1987, Phys. Rev. D, 35, 1151

________________________________. 1988, ApJ, 329, 572

Audouze, J., Lindley, D., & Silk, J. 1985, ApJ, 293, L53

Copi, C.J., Schramm, D.N., & Turner, M.S. 1995, Science, 267, 192

Dimopoulos, S., Esmailzadeh, R., Hall, L.J., & Starkman, G.D. 1988, ApJ, 330, 545

________________________________. 1989, Nucl. Phys., B331, 699

Domínguez–Tenreiro, R. 1987, ApJ, 313, 523

Duncan, D.K., Primas, F., Rebull, L.M., Boesgaard, A.M., Deliyannis, C.P., Hobbs, L.M.,
King, J.R., & Ryan, S.G. 1997, ApJ, 488, 338

García López, R.J., Lambert, D.L., Edvarsson, B., Gustafsson, B., Kiselman, D., & Rebolo,
R. 1998, ApJ, in press, and preprint astro–ph/9801167

Garnavich, P.M., et al. 1998, ApJ, 493, L53

Geiss, J., & Reeves, H. 1972, A&A, 18, 126

Jedamzik, K., Fuller, G.M., Mathews, G.J., & Kajino, T. 1994, ApJ, 422, 423

Krauss, L.M., & Kernan, P. 1994, ApJ, 432, L79

López–Suárez, J. 1997, PhD Thesis (Univ. Barcelona)

Malaney, R.A., & Fowler, W.A. 1988, ApJ, 333, 14
Malaney, R.A., & Mathews, G.J. 1993, Phys. Rep., 229, 145

Mathews, G.J., Schramm, D.N., & Meyer, B.S. 1993, ApJ, 404, 476

McCullough, P.R. 1992, ApJ, 390, 213

Orito, M., Kajino, T., Boyd, R.N., and Mathews, G.J. 1997, ApJ, 488, 515

Pagel, B.E., & Kazlaukas, A. 1992, MNRAS, 256, 49

Perlmutter, S., et al. 1998, Nature, 391, 51

Rauscher, T., Applegate, J.H., Cowan, J.J., Thielemann, F.–K., & Wiescher, M. 1994, ApJ, 429, 499

Schwitters, R.F. 1983, in Proc. 11th SLAC Summer Inst. on Part. Phys., preprint SLAC–0627, 115

Smith, V.V., Lambert, D.L., & Nissen, P.E. 1992, ApJ, 408, 262

Steigman, G. 1998, in Proc. 2nd Oak Ridege Symp. on Atomic & Nuclear Astrophysics, ed. A. Mezzacapa (Bristol: Inst. of Phys.), in press, and preprint astro–ph/9803055

Steigman, G., Hata, N., & Felten, J.E. 1998, ApJ, in press, and preprint astro–ph/9708016

Thomas, D., Schramm, D.N., Olive, K.A., & Fields, B.D. 1993, ApJ, 406, 569

Thomas, D., Schramm, D.N., Olive, K.A., Mathews, G.J., Meyer, B.S., & Fields, B.D. 1994, ApJ, 430, 291

Walker, T.P., Steigman, G., Schramm, D.N., Olive, K.A., & Kang, H. 1991, ApJ, 376, 51

Witten, E. 1984, Phys. Rev. D, 30, 271
Yepes, G., & Domínguez–Tenreiro, R. 1988, ApJ, 335, 3

This manuscript was prepared with the AAS \LaTeX{} macros v4.0.
Fig. 1.— Primordial D abundance as a function of the $\tau_x$, the half–life of the X–particles, for three different values of the volume fraction $f_v$: 0.074 (short–dashed line), 0.119 (long–dashed line), and 0.144 (dot–dashed line), and fixed values of the other parameters (see text for the meaning of the different symbols).
Fig. 2.— Primordial abundances of the light nuclides D, $^3$He, $^4$He, $^6$Li, $^7$Li, and $^9$Be, as
a function of the half–life of the X–particles, $\tau_x$, for fixed values of the other parameters:
$\eta_{10,f} = 18$, $f_v = 0.144$, $R = 5000$, $d/a = 10^{7.5}$, $r m_x = 10^{-5}$, and $r_B^* = 1.5 \times 10^{-12}$ (see text for the meaning of the different symbols). The two vertical dashed lines mark the boundaries of the interval where the predicted abundances are compatible with those observationally inferred.