CONSTRAINTS ON DARK MATTER FROM PRIMORDIAL NUCLEOSYNTHESIS

Jean AUDOUZE

Institut d'Astrophysique du CNRS, Paris, France
and Laboratoire René Bernas, Orsay, France.

ABSTRACT. Primordial nucleosynthesis which is responsible for the formation of the lightest elements (D, ^3He, ^4He and ^7Li) provides a unique way to determine the present baryon density ρ_B in the Universe and therefore the corresponding cosmological parameter Ω_B. After a brief summary of the relevant abundance determinations and of the consequences of the Standard Big Bang nucleosynthesis, it is argued that one needs to call for specific models of chemical evolution of the Galaxy in order to reconcile the observations with the predictions of this model. In this context the predicted values for Ω_B should range from 4 10^{-3} to 6 10^{-2}. These values are significantly lower than those deduced from current M/L determinations.

In order to reconcile the early nucleosynthesis with larger values of Ω_B (i.e. with the presence of dark matter) two scenarios departing from the Standard Big Bang models are presented : they are (i) the possible partial photofission of ^4He (and ^7Li) into D and ^3He induced by energetic photons coming from the decay of massive (500 MeV) neutrinos and/or gravitinos (ii) the existence of some semi baryonic form of matter referred to as "quark nuggets". In these two cases the formation of the very light elements could be consistent with values of Ω as large as 1, i.e. similar to those suggested by some of the determinations collected in this book and which are favoured by the current models of inflationary Universes.

1. INTRODUCTION

The paramount importance of the formation processes of the very light elements (D, ^3He, ^4He and ^7Li) in cosmology and in particular in the determination of the baryonic density of the Universe (and also of the maximum number of neutrino families) has been pointed out by a large number of papers, including e.g. Yang <u>et al</u>. 1984, Boesgaard and Steigman 1985, Audouze 1984. Primordial nucleosynthesis occurs at a time of about 100 sec after the critical event from which Big Bang

J. Kormendy and G. R. Knapp (eds.), Dark Matter in the Universe, 499–523.

originates and might constitute one of the most severe constraints regarding the presence of dark matter in the Universe.

This presentation starts with a brief review concerning the current status of the abundance determinations of the relevant elements. Then it is argued that if the primordial nucleosynthesis occurs according to the standard Big Bang model and is followed by the most classical galactic evolution models such as those used by Audouze and Tinsley (1974), the baryonic density deduced from the primordial ^{4}He abundance is significantly lower than that which come from the inferred primordial D. This why Delbourgo-Salvador et al. (1985) (see also Gry et al. 1983) have considered further galactic evolution models which lead to primordial abundances of D and ^{3}He in agreement with that of ^{4}He and provide a consistent range of values for the cosmological parameter Ω. However one should draw attention on the fact that the deduced value of Ω is significantly lower than that inferred in other papers. For instance Boesgaard and Steigman (1985) quote $0.014<\Omega<0.19$. After a discussion concerning this discrepancy, this presentation ends with two proposals for reconciling the early nucleosynthesis with larger values of Ω. The first one concerns some possible partial photofission of ^{4}He (and ^{7}Li) into D and ^{3}He which could be triggered by the decay of massive (500 MeV) neutrinos and/or gravitinos (as suggested by Audouze et al., 1985). The second calls attention on the possible existence of heavy "quark nuggets" which may come naturally from quantum chromodynamic theories (Witten 1984) and which could constitute the most abundant form of existing matter (Schaeffer et al., 1985).

2. ABUNDANCE DETERMINATIONS OF THE LIGHT ELEMENTS

The abundances of D, ^{3}He, ^{4}He and ^{7}Li have been thoroughly measured and analyzed in a large number of articles. References can be found in Audouze 1982 and 1984, Boesgaard and Steigman 1985 and in the conference proceedings edited by Shaver et al.in 1984.

2.1. Deuterium

The deuterium abundance can be determined either in the interstellar medium from its UV (950 Å) Lyman line (see e.g. Vidal Madjar et al., 1984) or in the solar system mainly through the determination of the ^{3}He/^{4}He ratio in the solar wind (Geiss and Reeves 1972). The interstellar D/H ratio is about $(1\pm0.5)\ 10^{-5}$. These abundances are therefore still quite uncertain mainly because of the complexity of the interstellar lines of sight. Moreover because D is a very fragile nuclear species (it is transformed into ^{3}He in H rich regions at T> a few 10^5K) its abundance is very dependent on the stellar and galactic evolution.

2.2. ^{3}He

The ^{3}He abundance is determined in the solar system also in the solar wind and in some gas rich meteorites ^{3}He/H$\sim$1.4±0.4 10^{-5} (D+^{3}He/H$\sim$ 3.6±0.6 10^{-5}). Rood et al. 1984 have attempted to determine the interstellar ^{3}He$^+$/^{4}He abundance by observing the 8.7 GHz line of ^{3}He$^+$ in a few galactic H II regions. The corresponding ^{3}He/H ratios range from less than 2 10^{-5} (for W49 and M17A) to 5 10^{-4} for W3. This very large variation of the ^{3}He/H ratio from one H II region to another clearly shows that this interstellar abundance is still badly determined. Because ^{3}He is the out-product of D, its abundance depends also much on the stellar and galactic evolution.

2.3. ^{4}He

The ^{4}He abundance has been observed in astrophysical sites as different as the Sun and Jupiter, the solar wind, the stellar atmospheres, planetary nebulae, the globular clusters and the HII regions of blue compact galaxies (see e.g. the book of Shaver et al., 1984). The most often adopted primordial ^{4}He abundance comes from the analysis of Kunth and Sargent (1984), i.e. Y$\sim$0.245±0.005. Given the cosmological importance of an accurate determination of this abundance (see following sections) two remarks should be made at this point : (i) Given the large spread of the abundances observed in blue compact objects, the uncertainty on the primordial He abundance deduced by Kunth and Sargent 1984 might be larger than that quoted by these authors (ii) Davidson and Kinman (1985) have made a careful analysis of the He abundance in IZW18 and deduce from their analysis a value Y$\sim$0.23±0.02 (iii) Vigroux et al. (1985) have shown recently that one could deduce a primordial Y_p value of 0.24 from the He/H versus O/H correlation but a much lower value of 0.20 from the He/H, N/O correlation. I do not claim here that Y_p has such a low value but I do want to call attention on the fact that this primordial value is still uncertain (at least more than what is quoted in the current literature).

2.4. Lithium 7

Spite and Spite (1983) who analyzed the Li abundance in population II stars deduce from it a primordial Li abundance of (^{7}Li/H)$\sim$$10^{-10}$, i.e. ten times lower than its value in some young F stars and in the solar system. Given the fact that convection and diffusion processes which could affect the atmosphere composition of such stars are not yet properly understood it might be still possible that the primordial Li/H ratio is as high as 10^{-9} as previously thought e.g. by Reeves 1974.

Table 1 provides our estimates of the interstellar, solar system and primordial abundances of the relevant light elements. As said above, the primordial abundances of D and ^{3}He are very dependent on the galactic evolution models and will be discussed in section 4.

Element	Primordial Abundance	Solar system Abundance	Interstellar abundance
D	$3\ 10^{-5}$-$3\ 10^{-4}$	$(3\pm1)10^{-5}$	$3\ 10^{-6}$-$2\ 10^{-5}$
^{3}He	$2\ 10^{-5}$-$6\ 10^{-5}$	$(4\pm2)10^{-5}$	$4\ 10^{-5}$-$2\ 10^{-4}$
^{4}He	0.22 - 0.25	0.15-0.24	0.22 - 0.30
^{7}Li	$(6\pm0.3)10^{-10}$	$\sim10^{-8}$	$7\ 10^{-10}$-$2\ 10^{-9}$

TABLE 1.
Abundances (by mass) of the light element produced by the primordial nucleosynthesis

3. THE CONSEQUENCES OF THE STANDARD MODEL

The primordial nucleosynthesis occuring under the assumptions made by the Standard (also called canonical) model has been thoroughly discussed in the literature (see e.g. Audouze 1984, Yang et al. 1984, Boesgaard and Steigman 1985). Figure 1 taken from Yang et al. (1984) displays the well known dependence of the primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li with the baryonic density $\eta=n_B/n_\gamma$ (where n_B and n_γ are respectively the baryon and photon densities). I will only remind that two important parameters can be deduced from this model : (i) the maximum number of neutrino (or lepton) families especially sensitive to the primordial abundance of ^{4}He (Y_p) : an increase (or a decrease) of Y_p by 1% corresponds to an increase (or a decrease) of this number by one unit : If $Y_p<0.23$ and $N_\nu<2$, one can see on Figure 2 that such a low Y_p (which cannot be ruled out by the present observations) would imply very large D_p values (and therefore very low baryonic densities as we will see below) and that neutrinos can exist only at most in two separate components (the tau neutrino ν_τ should therefore be considered as a mixture of the ν_e and ν_μ states). If $Y\sim0.24\pm0.010$ there is of course a very good agreement between the "canonical" primordial nucleosynthesis and the three families of neutrinos. This agreement is invoked as an argument in favour of Grand Unification Theory schemes which relate the three lepton families to the three quark families (see e.g. Fayet 1984).

(ii) We are especially concerned here by the constraints put by the canonical primordial nucleosynthesis on the present baryonic

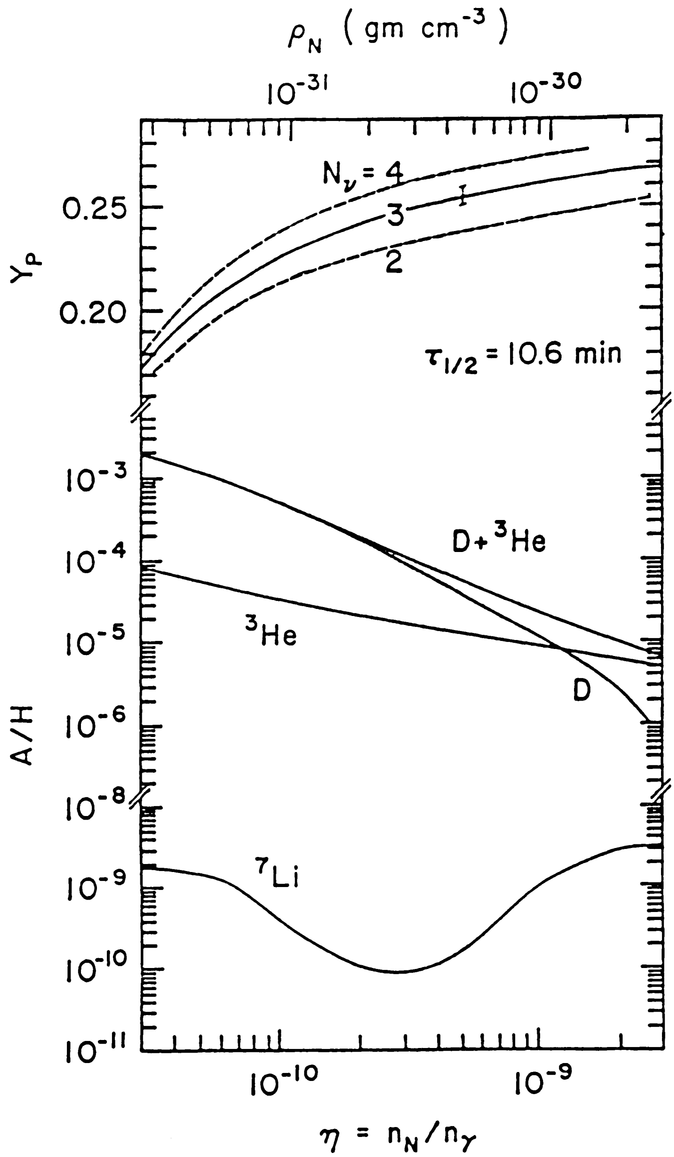

Figure 1

Abundances of D, ^{3}He, ^{4}He and ^{7}Li predicted by the Standard Model (see text) against the baryon to photon ratio η. The three curves for the ^{4}He abundance (Y) correspond respectively to 2, 3 and 4 different neutrino families (from Yang et al., 1984).

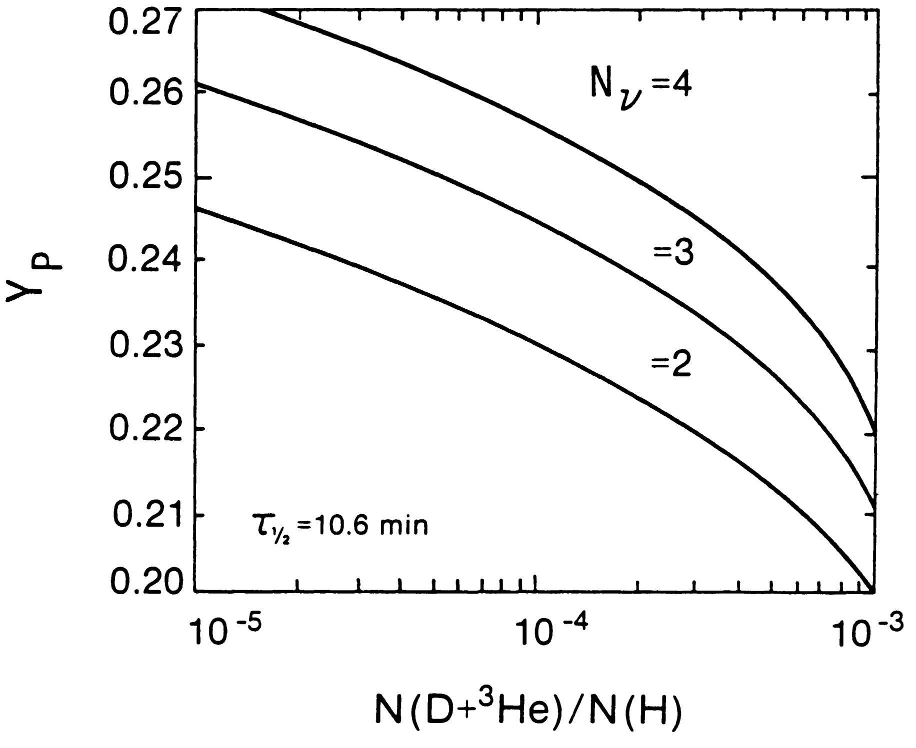

Figure 2

Predicted ^{4}He abundance (Y_p) against the predicted N(D + ^{3}He) abundance for 2, 3 and 4 different neutrino families (from Yang *et al.*, 1984). This diagram shows that if Y_p<0.22 the Standard Model runs into difficulty.

https://doi.org/10.1017/S0074180900150788 Published online by Cambridge University Press

density of the Universe and therefore on its overall dynamics : given the critical density $\rho_c=3H_0{}^2/8\pi G=1.88\ 10^{-29}h_0{}^2 gcm^{-3}$ (h_0 is the Hubble constant H_0 expressed in units of 100 kms^{-1} Mpc^{-1}) corresponding to a flat Universe and to a cosmological parameter $\Omega=1$, Ω_B (the baryonic cosmological parameter)$=3.53\ 10^{-3}\ h_0{}^2\ \theta^3\ \eta_{10}$ ($\theta=T/2.7K$, $\eta_{10}\ 10^{10}\ \eta$). Boesgaard and Steigman 1985 following Yang et al. (1984) consider that there is a good agreement between the primordial abundances deduced from observations and those calculated for $3<\eta_{10}<10$ which leads to $0.01<\Omega_B<0.19$. This estimate is clearly less than that inferred from the dynamics of large structures $\Omega\geqslant0.3$ but is consistent with the values of Ω deduced from the dynamics of small groups of galaxies. Should the cosmological parameter Ω be larger than 0.2 either to account for large M/L ratio determinations or to satisfy the inflationary scenarios according which $\Omega=1$, there should be a significant fraction of the matter in non-baryonic form.

In contrast with the optimistic view presented by Yang et al. (1984) who argue in favour of such a good agreement, one may give credit to the point made by Vidal-Madjar and Gry 1984 who claim that the comparison between the observational deductions and the calculations regarding D and ^{4}He respectively may lead to discrepant values of η. This is the case if Y_p ranges between 0.22 and 0.25 and if only 30% to 70% of D is destroyed during the galactic history as it has been evaluated by Audouze and Tinsley 1974 in the frame of simple models of chemical evolution of galaxies. This is the reason why we have examined somewhat different models of that type in order to examine what could be the necessary conditions to restore such an agreement.

4. CHEMICAL EVOLUTION OF D AND ^{3}He AND PRIMORDIAL NUCLEOSYNTHESIS

This section is a brief account of the analysis of some models of galactic evolution concerning D and ^{3}He recently proposed by Delbourgo-Salvador et al. 1985. While ^{7}Li and especially ^{4}He are not as significantly affected by such processes, it is possible to design some models leading to the destruction of most of the primordial D during the galactic history.

Two types of models have been considered :

(i) the possibility of admixture (by infall or inflow) of stellar processed (i.e. D free) material in the considered galactic zone.

(ii) the mass loss of D free material released during the pre main sequence phase,

(i) Figures 3a and 3b shows the galactic evolution of D, ^{3}He and ^{4}He computed with type (i) models in which the astration rate $\nu=0.45$ (expressed in units of 10^9 year^{-1}), the admixture rate of D free material $\delta=0.12$ (M$\odot$ per unit of 10^9 M$\odot$) and the rate of ^{3}He stellar production being respectively $5\ 10^{-5}$ $(M/M\odot)^{-4}$ (fig. 3a) and $5\ 10^{-4}$ $(M/M\odot)^{-4}$ (fig. 3b) : this parametrization takes into account the fact that more massive stars are likely to have hotter inner regions inside

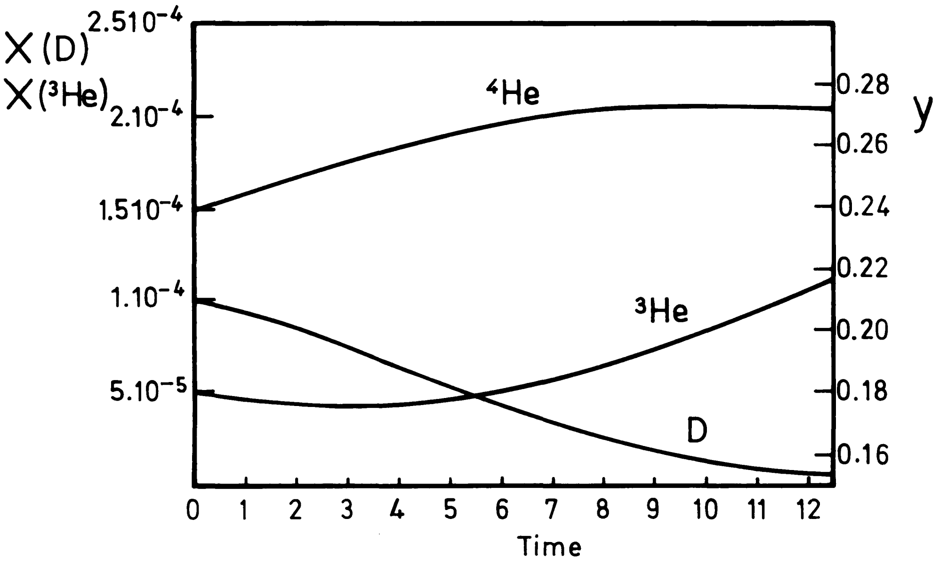

Figure 3a
Abundances (by mass) of D, ^{3}He and ^{4}He as a function of time (in 10^9 years units) calculated with type (i) (see text) models where there is some infall of processed material such that the ^{3}He production rate is 5 10^{-5} (M/Mo)$^{-4}$ (from Delbourgo-Salvador et al., 1985).

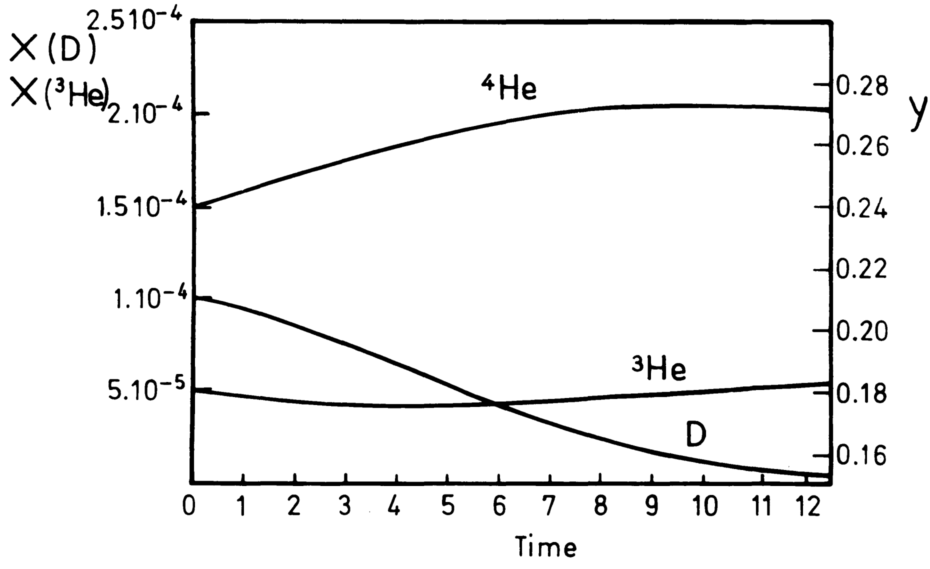

Figure 3b

Abundances (by mass) of D, ^{3}He and ^{4}He as a function of time (in 10^{9} years units) calculated with type (i) (see text) models where there is some infall of processed material such that the ^{3}He production rate is 5 10^{-4} $(M/Mo)^{-4}$ (from Delbourgo-Salvador et al., 1985).

which ^3He can itself be transformed into ^4He. With such models $D^{Now}/D_{prim} \sim 15$, a present interstellar value of D/H$\sim$5 10^{-6} as found by Vidal-Madjar et al., (1983) would be consistent with a solar system value of $\sim 10^{-5}$ and a primordial value of $\sim 10^{-4}$ while $^3He/H$ which could be 5 10^{-5} at the beginning of the galactic life would be about 5 10^{-5} in the interstellar medium in case (a) and 1.2 10^{-4} in case (b). Large values of the rate of stellar production of ^3He might explain the large ^3He interstellar abundances observed by Rood et al., 1984.

(ii) If stars suffer large mass losses during their pre main sequence phase they could release significant amounts of D free-^3He rich material which could then affect the galactic evolution of these two isotopes. The temperature reached by such material is indeed sufficient to destroy D into ^3He. Figure 4 shows the evolution of D, ^3He and ^4He computed with a model where we assume that stars in average lose about 20% of their mass during the pre main sequence phase and where the rate of stellar ^3He production is 5 10^{-5} $(M/M_\odot)^{-4}$. In such models D evolves in a quite similar fashion as the previous ones while the present (interstellar) $^3He/H$ abundance is about the same as that computed in model (i) with a rate of 5 10^{-4} $(M/M_\odot)^{-4}$.

These two types of models alleviate the difficulty encountered in simple models which imply primordial D abundances which could be inconsistent with the primordial ^4He abundance.

If we adopt such models of galactic evolution together with the standard primordial nucleosynthesis scheme, we can find a range of baryonic density η consistent with the primordial abundances deduced from these models. The primordial abundance ranges of D, ^3He, ^4He and ^7Li are respectively 3 $10^{-5} \leq X(D) \leq 3$ 10^{-4}, 3 $10^{-5} \leq X(^3He) \leq 6.10^{-5}$, $0.235 \leq T \leq 0.255$ and 5 $10^{-10} \leq X(^7Li) \leq 2$ 10^{-9} (where the abundances are expressed by mass). Figure 5 shows that η_{10} can range from 1.2 to 4.5 which means that $0.004 \leq \Omega_B \leq 0.06$. The baryonic cosmological parameter deduced from our analysis is significantly smaller than the one of Yang et al., 1984 who derive $0.014 \leq \Omega_B \leq 0.19$. Our Ω_B value falls about also below the Ω values deduced from large scale dynamics. The present derivation implies that a large fraction of the matter present in the Universe should be in a non baryonic form.

5. PARTIAL PHOTODISINTEGRATION OF ^4He (AND ^7Li) BY ENERGETIC PHOTONS

As said before the standard primordial nucleosynthesis with or without galactic evolution effects puts severe constraints on the baryonic density and possibly on the cosmological parameter Ω and therefore on the overall evolution of the Universe. This constraint comes mainly from the fact that D and ^3He are very underabundant in Universes such that $\rho_{present} \simeq \rho_{critical}$. In this section, we review the first scenario that we (i.e. David Lindley, Jo Silk and myself)[1] have

[1] More detail can be found in Audouze, Lindley and Silk, 1985.

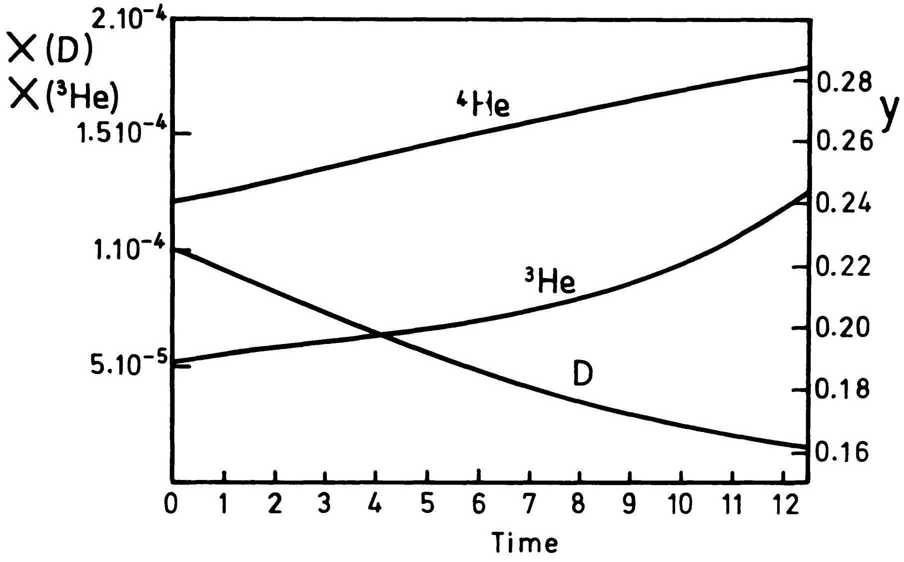

Figure 4

Abundances (by mass) of D, ^{3}He and ^{4}He as a function of time (in 10^9 years units) calculated with type (ii) (see text) models where mass loss processes suffered by pre main sequence stars which release D free, ^{3}He rich material are taken into account. Here 20% of the stellar mass is involved in this process (from Delbourgo-Salvador *et al.*, 1985).

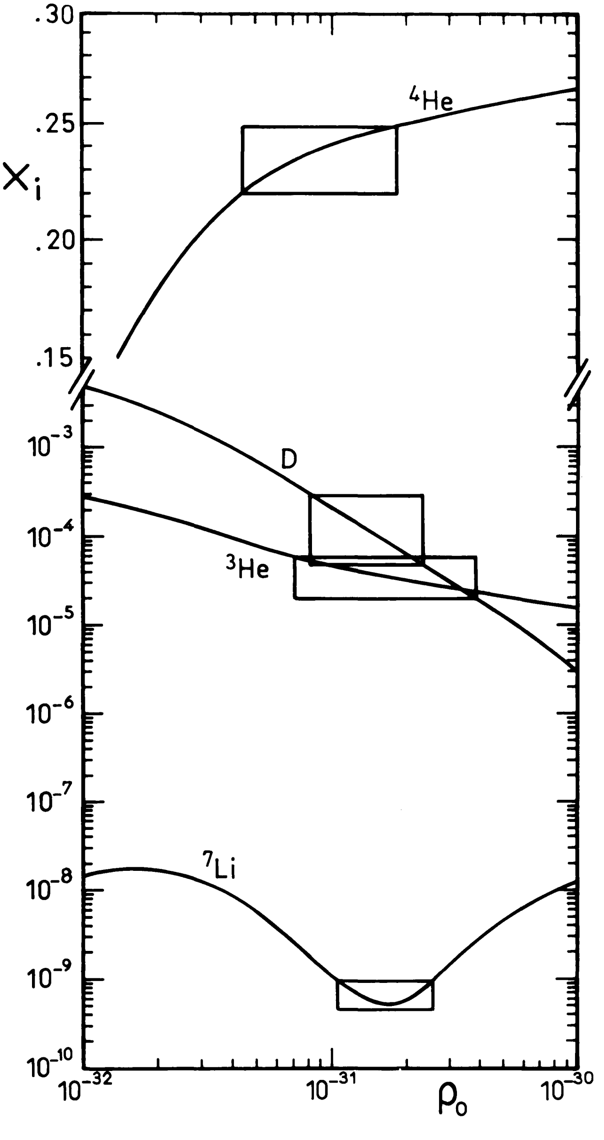

Figure 5 Comparison between the light element abundances computed by Delbourgo-Salvador *et al.*, 1985 and the primordial abundances of D, ^{3}He and ^{4}He taking into account the effects of galactic evolution estimated by these authors. One deduces from this comparison that $4\ 10^{-3} < \Omega_B < 6\ 10^{-2}$ (from Delbourgo-Salvador *et al.*, 1985).

sketched in order to reconcile the production of these elements with a large baryonic density. For that purpose we assume that ^{4}He (and possibly also ^{7}Li) are partially photodisintegrated by energetic photons coming from massive unstable particles.
Two different hypothetical candidates have been considered :
(i) massive neutrinos with a mass $\geqslant$500 MeV as already envisaged by Audouze and Silk (1984) (see also Lindley, 1979 and Hut and White, 1984),
(ii) gravitinos which are the leptons of spin 3/2 associated to the gravitons (of spin 2) in the supersymetric theories (see e.g. Fayet 1984) and the life time of which $\tau_{3/2} \sim m_{pl}^2/m_{3/2}^3$ i.e. $\sim 10^8$ (100 $GeV^{-3}/m_{3/2})^{-3}$ sec where m_{pl} is the Planck mass and $m_{3/2}$ the mass of the gravitino.

The high energy photons which are produced by the decay of such particles can either (a) scatter on thermal photons (i.e. the photons which constitute the background cosmological radiation) and they can produce e^-e^+ pairs if the product of thermal energy by the energy of the photons is higher than a threshold value computed by Lindley (1985) such that

$$E_\gamma . kT = \frac{1}{50} \, MeV^2 \qquad (1)$$

(b) if the product is lower than this threshold value the energetic photons coming from the decay can suffer some Compton scattering on electrons, induce pair production by interaction with nuclei or induce some photofission. In situation (a) thermalization is too rapid for photofission to take place. This implies that kT should be at least lower than 10^{-3} MeV for the decay photons to have an energy >20 MeV (which is the threshold energy of partial photofission of ^{4}He). The consequence is that the life time of these gravitinos or massive neutrinos should be $\geqslant 10^5$-10^6 sec.

The evolution of the abundances of the very light elements can be written as :

$$\begin{aligned} dN_4 &= -\Sigma_4 N_4 dn_E/n_e \\ dN_3 &= (-\Sigma_3 N_3 + f_{43}\Sigma_4 N_4) dn_E/n_e \qquad (2) \\ dN_2 &= (-\Sigma_2 N_2 + f_{32}\, \Sigma_3 N_3 + f_{42}\Sigma_4 N_4) dn_E/n_e \end{aligned}$$

N_2, N_3 and N_4 are respectively the abundances of D, ^{3}He and ^{4}He, the Σ are the corresponding rates, the fij are the branching ratios, n_E is the density of energetic electrons. These electrons are the secondary particles coming from the energetic photons and Lindley (1985) has shown that it is equivalent to write these equations with electrons since photons behave like two electrons of half the energy. Finally n_e is the thermal electron density.

Figures 6 and 7 show respectively the effect of gravitinos and of massive unstable neutrinos on the light element abundances. One can see that there is a range of mass and lifetime for such particles

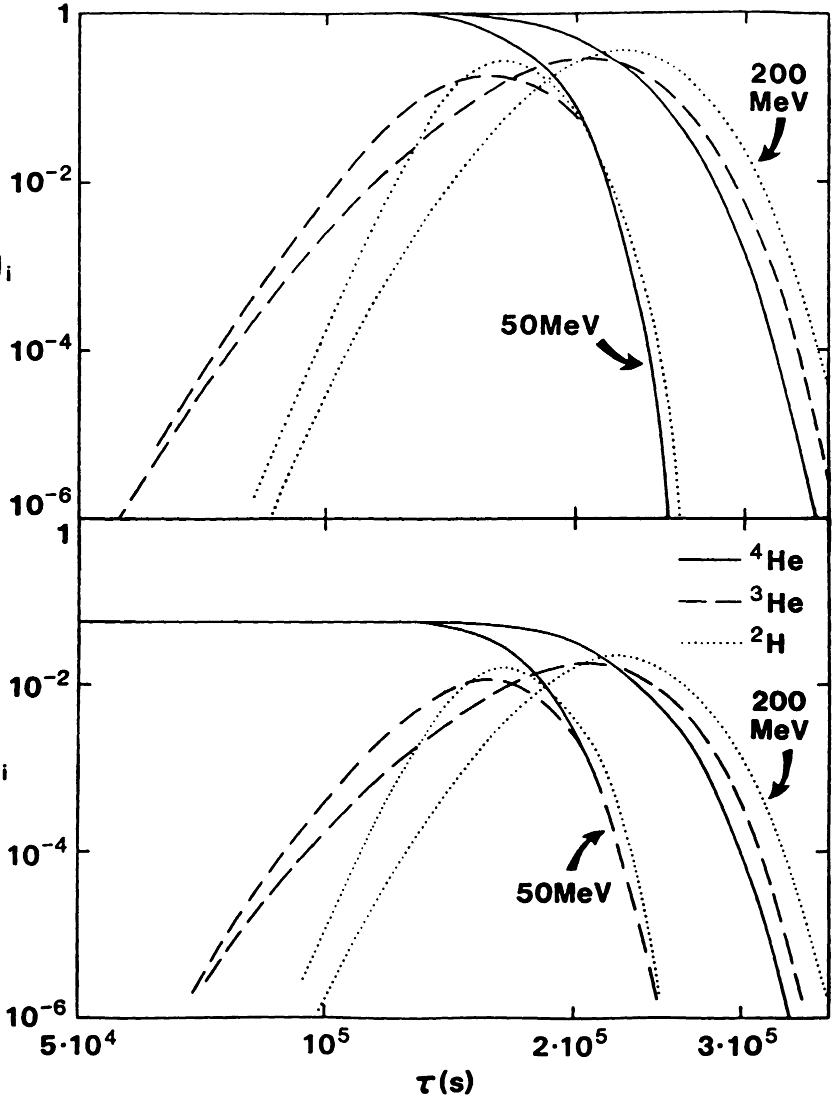

Figure 6

Effect of decaying gravitinos inducing partial photofission of ^{4}He (and also ^{3}He and D). The upper panel corresponds to $Y_{initial}=1$ while the lower panel corresponds to $Y_{initial}=0.24$ with no initial D and ^{3}He. Calculations have been performed per 50 MeV and 200 MeV electrons. The resulting abundances are plotted against the gravitino lifetime (from Audouze et al., 1985).

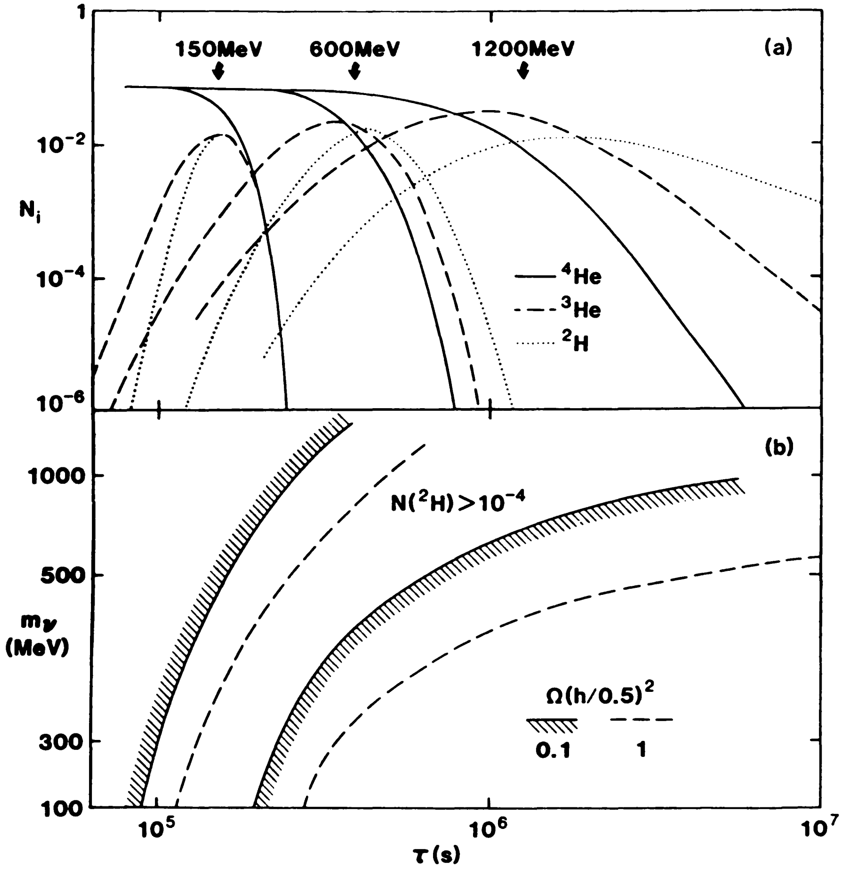

Figure 7

Same calculations for decaying massive neutrinos. The upper panel shows the resulting D, ^{3}He and ^{4}He abundances from 3 different values of the neutrino mass (150 MeV, 600 MeV and 1200 MeV) and $Y_{initial}$=0.28. The lower panel shows the domain neutrino mass (m_ν) neutrino lifetime (τ_s) inside which significant D abundances can be reached (from Audouze et al. 1985).

which induce photofission processes in order that the predicted D, ^{3}He and ^{4}He abundances are consistent with their primordial abundances (figure 6 and 7). The existence of these particles at the beginning of the evolution of the Universe may reconcile a dense (probably closed) Universe with the observed abundances of the light elements.

6. EFFECT OF QUARK NUGGETS ON THE PRIMORDIAL NUCLEOSYNTHESIS

Among the many hypotheses which have followed the irruption of particle physics in cosmology and especially the occurence of the unification theories, it is interesting to consider the scenario proposed by Witten (1984) who argued in favour of the existence of "quark nuggets" aside from that of nuclei. These particles would be made from an equal number of u, d and s quarks. They could have appeared at a time when the temperature of the Universe was $T \sim 100$ MeV by a first order quark-hadron phase transition : if this transition occurs smoothly, these nuggets could coexist with nucleons after the nucleation (see Witten, 1984, for details). For a quark nugget made of 3A quarks (A being the atomic mass of such particles), its radius is $r = r_0 A^{1/3}$, its volumic mass is comparable to that of the nuclear matter and its electric charge is $Z \sim 5 A^{1/3}$. These particles, if they exist, have interesting properties : (i) they could populate the "nuclear desert" which ranges from $10^3 < A < 10^{57}$ (10^3 corresponding to the largest atomic mass for nucleons and 10^{57} to that of a neutron star considered as a single particle, (see e.g. de Rujula 1984) ; (ii) when they are accelerated they might trigger "Centauro" events : these events which have been detected in nuclear emulsion chambers at high altitude are very energetic $10^{15\pm1}$ ev, they produce many (70-100) secondary particles but no (or very few) π_0 (Kazanas et al. 1985). They might be present in the very high energy component of the cosmic rays (Audouze et al. 1985b); (iii) the properties of the high energy cosmic rays coming from the direction of Cygnus X3 might be due to the presence of such still hypothetical particles see e.g. Barnhill et al., 1985.

Here we are concerned by their possible effect on the primordial nucleosynthesis. In other words, if such particles exist it possible to be in at flat ($\Omega=1$) or a close ($\Omega>1$) Universe and still make predictions on the production of D, ^{3}He, ^{4}He and ^{7}Li consistent with their presently adopted primordial abundances. As analysed by Schaeffer et al., 1985, these nuggets s can interact with nucleons n and p through reactions $n+s \rightleftarrows s$ and $p+s \rightleftarrows s$ within specific conditions which depend on the stability of these nuggets and their absorption and emission properties. The nucleon absorption rates are respectively $\lambda(n+s \to s) = \tau_0 \langle v \rangle \ \rho_B 1/A$ and $\lambda(p+S \to 1) = \tau_0 \langle v \rangle \rho_B \ f_c 1/A$ for the neutrons and the protons. In these expressions τ_0 is the geometrical cross section $\tau_0 = \pi R^2$; $\langle v \rangle$ is the relative velocity of the nuggets and the nucleons (averaged over the Maxwell-Boltzmann distribution of these particles), ρ_B is the baryonic density, A the atomic mass of the nugget and f_c the Coulomb barrier that a proton has to overcome before its absorption (f_c=exp $-\varepsilon c/kT$ where ε_c is the Coulomb energy of the proton inside the nugget electrical field). These expressions hold for stable nuggets. If these particles are unstable these rates should be multiplied by a factor f_B which is a barrier, the height of which is fixed by the binding energy ε of the nucleon inside the nugget such that $f_B = \exp(-\varepsilon/kT)$ ($\varepsilon \sim 10$-100 MeV).

To summarize : (3)

λ_n stable$=\tau_o\langle v\rangle\rho_B 1/A$ λ_n unstable$=\tau_o\langle v\rangle\rho_B f_B 1/A$

λ_p stable$=\tau_o\langle v\rangle\rho_B f_c 1/A$ λ_p unstable$=\tau_o\langle v\rangle\rho_B f_c f_b 1/A$

For the <u>emission of nucleon</u> s→n+s and s+p+s the corresponding rates are :

$$\lambda_n \text{ stable} = \frac{\eta c}{R} f_B \frac{1}{A} \qquad \lambda_n \text{ unstable} = \frac{\eta c}{R}\frac{1}{A}$$

$$\lambda_p \text{ stable} = \frac{\eta c}{R} f_B\, f_c\, \frac{1}{A} \qquad \lambda_p \text{ unstable} = \frac{\eta c}{R}\frac{1}{A} f_c \tag{4}$$

In these expressions, the term $\eta c/R$ is similar to a fission barrier : it represents the frequency of attempts for the nucleon (proton or neutron) to go out of the nugget multiplied by an energy barrier factor.

After the phase transition which took place at T=100 MeV between nucleons and nuggets, the relative density of these two classes of particles is governed by

$$\frac{d}{dt}\frac{\Omega_B}{\Omega} = \frac{\Omega_S}{\Omega}\lambda_{em} - \frac{\Omega_B}{\Omega}\lambda_{abs} \tag{5}$$

($\Omega=\Omega_B+\Omega_S$) : Ω_B is the mass fraction made of baryons while Ω_S is the one made of nuggets from the above expressions, $\lambda_{em}= n\,\frac{c}{R}\,\frac{1}{A}$ $\sim n_Q\ A^{-4/3}$ where n_Q is the baryon number density within a nugget ($n_Q \sim 10^{39}$ cm^{-3}). $\lambda_{abs} \sim \Pi\ R^2\ n_S\ \langle v\rangle \sim \Omega_{nug}\ n_c A^{-1/3}$ where n_c is the critical density of the Universe ($\sim 10^{23}$ cm^{-3}) at the time of nucleosynthesis. The comparison of these two terms in (5) clearly shows that the process of baryon emission is much more important than that of absorption for not too large values of A :

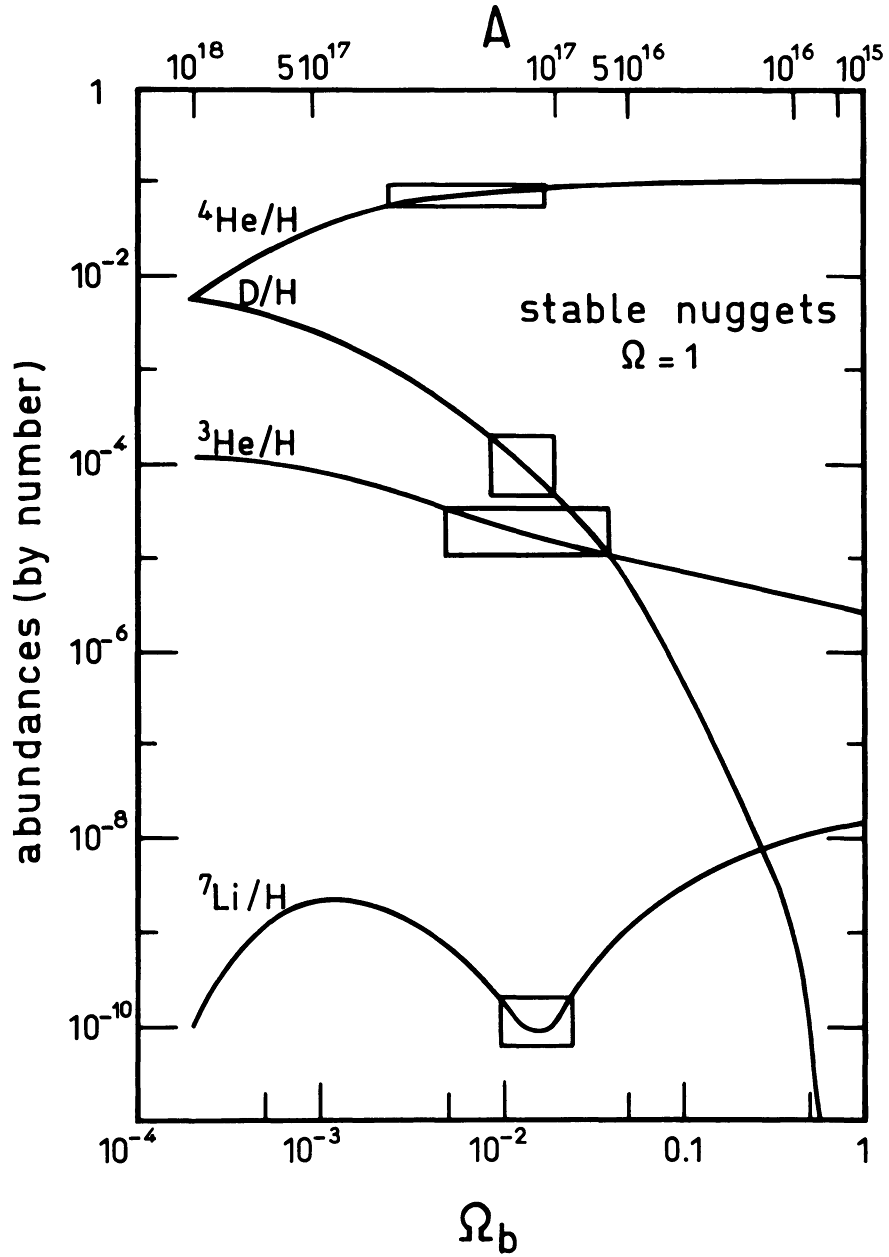

Figure 8

Primordial abundances calculated from a model for which Ω=1 and including stable quark nuggets. If these nuggets have atomic masses $\sim 10^{17}$, the results of the Big Bang nucleosynthesis can be consistent with a closed universe (from Schaeffer et al., 1985).

https://doi.org/10.1017/S0074180900150788 Published online by Cambridge University Press

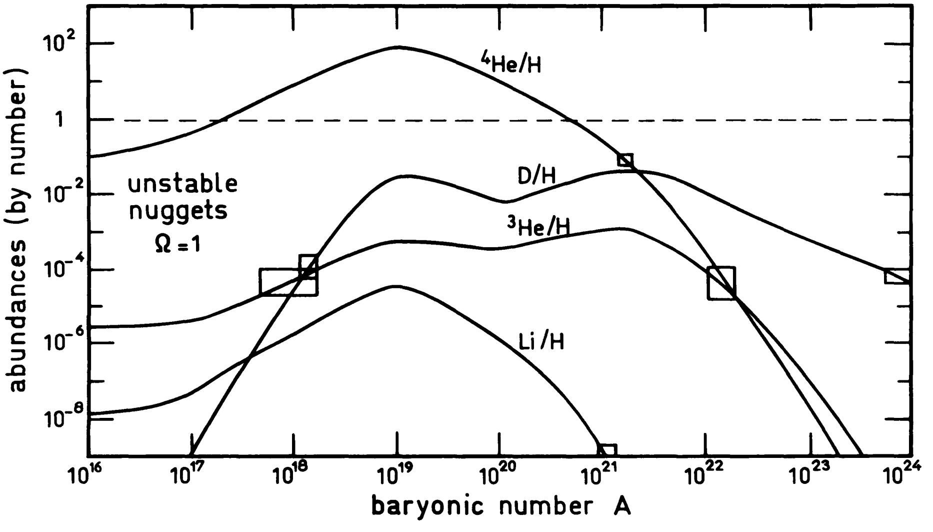

Figure 9

Primordial abundances calculated from a model for which Ω=1 including instable quark nuggets. The agreement between observations and calculations which is achieved for stable nuggets does not exist in this case (from Schaeffer *et al*., 1985).

https://doi.org/10.1017/S0074180900150788 Published online by Cambridge University Press

(1) In the case of stable or metastable quark nuggets the solution of (5) can be written as :

$$\frac{\Omega_b}{\Omega} = 1-e^{-x}$$

with $x = \int_0^\infty \lambda_{em}\, dt = \left(\frac{A}{A_{tran}}\right)^{-4/3}$

with A_{tran} (the transition atomic mass) such that

$$A_{tran} = 1.6\ 10^{16} \left(\frac{\varepsilon}{10\ \mathrm{MeV}}\right)^{-3/2} \eta^{3/4}$$

for example $A_{tran}=2.10^{15}$ if $\varepsilon=10$ MeV and $\eta=0.1$

For $A<A_{tran}$ the nuggets are rapidly transformed into nucleons by the emission process while the number of nucleons become insignificant at $A\geqslant 10^{18}$. Figure 8 shows the outcome of the primordial nucleosynthesis calculated in a model of Universe for which one assumes that $\Omega=1$ (flat Universe) and where the stable quark nuggets exist with an atomic mass A which is the free parameter. One notices that if $A\sim 10^{17}$ there is a good agreement between the prediction of this model and the selected primordial abundances of D, ^3He, ^4He and ^7Li.

(2) If the quark nuggets are unstable, the rates of emission and absorption are of course modified along the lines described above. The equilibrium between the nuggets and the nucleons remain qualitatively the same. Namely the nucleons overcome the nuggets at low A and the situation is reversed at high A : for $A<10^{16}$, the nucleons dominate and the nucleosynthesis occurs like in the standard model; for $10^{16}<A<10^{22}$ there is a significant emission of nucleons coming from the decay of nuggets during the nucleosynthesis phase (at times corresponding to $10^8<T<10^9$ K) which increase significantly the light element production (fig. 9); for $A>10^{22}$ the Universe is made only from nuggets the neutron release occur ar lower temperatures than in the case considered by the standard model. There is a large difference between this case and the one concerning the stable nuggets. Because the emission rate is significantly larger and leads to a huge neutron release which is responsible for an overproduction of D, ^3He and ^4He (fig 9) there is no more agreement between the observations and the predictions of this model. Therefore if quark nuggets exist (see Alcock and Farhi, these proceedings for a rather pessimistic view regarding their evolution) they should be stable and have an atomic mass $A\sim 10^{17}$ in order to reconcile very satisfactorily the standard Big Bang nucleosynthesis with a significant presence of dark matter in the Universe.

7. SUMMARY AND CONCLUSIONS

Although the determinations of the primordial abundances of the very light elements D, ^{3}He, ^{4}He and ^{7}Li are quite uncertain for various reasons, current models of primordial nucleosynthesis are able to fix important cosmological constraints especially on the present baryonic density of the Universe and also on the number of different existing neutrino (and lepton) families. By using models of chemical evolution of our Galaxy like those with inflow of processed matter or with significant stellar mass losses occuring during the pre-main sequence phase (as designed by Delbourgo-Salvador et al., 1985) we were able to set conditions by which the $D_{primordial}/D_{present}$ ratio can be as large as ~10 and therefore find a range of baryonic densities consistent with all the present determinations of primordial abundances. We have deduced a range of baryonic cosmological parameter $4\ 10^{-3} \leq \Omega_B \leq 0.06$ significantly smaller than that one deduced e.g. by Yang et al., 1984 for whom $0.01 \leq \Omega_B \leq 0.19$. If our conclusions are confirmed it would mean that non baryonic matter should be invoked to explain large scale dynamic features such as those governing large clusters. Although one can still play with the uncertainties on the primordial abundances, on the actual value of the Hubble constant, on the neutron life time or on the values of the cosmological constant, the standard Big Bang model of primordial nucleosynthesis does imply a quite severe limitation on the baryonic dark matter.

We have also examined a few hypotheses such that Universes with large Ω parameter could be consistent with the primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li. The two scenarios reviewed here which fulfill that purpose invoke respectively the photofission of ^{4}He (and ^{7}Li) induced by energetic photons coming from the decay of gravitinos and/or massive neutrinos (Audouze et al., 1985a) or the presence of stable quark nuggets of atomic stars $A \sim 10^{17}$. In the first case (gravitinos and/or massive neutrinos) the dark matter which could lead to large Ω values may be consistent with current inflationary schemes) could be baryonic while in the second case most of it would be made of these still hypothetical quasi baryonic particles. In any case these two scenarios do not exhaust other possibilities to escape the strong constraint on the present baryonic density of the Universe coming from the Standard Big Bang nucleosynthesis. Cosmologists have enough imagination to design other elaborate and ingenious ways to solve the problems which are presently put to us by the observable Universe.

This review is based on investigations performed with several collaborators whom I am enjoying to work with. They are Pascale Delbourgo-Salvador, Cécile Gry, David Lindley, Guy Malinie, Richard Schaeffer and Jo Silk. I would like to thank also Elisabeth Vangioni-Flam and Alfred Vidal-Madjar for many interesting discussions on these topics. Most of the writing of this review presentation has been made at the Astronomy Department of U.C. Berkeley. I thank Jo Silk for his hospitality. I want also to express my gratitude to M.C. Pelletan for her careful typing of this paper.

REFERENCES

Alcock, C., Farhi, E., 1985, Phys. Rev. D., submitted and these proceedings
Audouze, J., 1982, in Astrophysical Cosmology, Eds H.A. Brück, G.V. Coyne and M.S. Longair, Pontificiae Academical Scientiarum Scripta Varia, p.395
Audouze, J., 1984, in Large Scale Structure of the Universe, Cosmology and Fundamental Physics, Eds G. Setti and L. Van Hove (Geneva CERN), p.293
Audouze, J., Lindley, D., and Silk, J., 1985, Ap.J. Letters, 293, L53
Audouze, J., and Silk, J., 1983, in Primordial Helium, Eds P. Shaver, D. Kunth and K. Kjär (ESO Garching) p.71
Audouze, J., Schaeffer, R. and Silk, J., 1985, 19th ICRC La Jolla USA, 8, 290
Audouze, J. and Tinsley, B.M., 1974, Ap.J., 192, 487
Barnhill, M.V., Gaisser, T.K., Stanev, T. and Halzen, F., 19th ICRC La Jolla, USA, 1, 99
Boesgaard-Merchant, A. and Steigman, G., 1985, Ann. Rev. Astron. Astrophys. in press
Davidson, K. and Kinman, T.D., 1985, Ap.J. Suppl., 58, 321
Delbourgo-Salvador, P., Gry, C., Malinie, G. and Audouze, J., 1985, Astron. Astrophys., 150, 53
De Rujula, A., 1984, CERN-Th 3980-84 preprint
Fayet, P., 1984, in Large Structure of the Universe, Cosmology and Fundamental Physics, Eds G. Setti and L. Van Hove (Geneva CERN) p.33
Geiss, J. and Reeves, H., 1972, Astron. Astrophys., 18, 126
Gry, C., Malinie, G., Audouze, J. and Vidal-Madjar, A., 1983, in Formation and Evolution of Galaxies and Large Structures in the Universe, Eds J. Audouze and J. Tran Than Van, Reidel Dordrecht, p.279
Hut, P. and White, S.D.M., 1984, Nature, 310, 637
Kazanas, D., Balashbhramanian, V.K., Streitmatter, R.E., 1985, Phys. Letters B, in press
Kunth, D., and Sargent, W.L.W., 1984, Ap.J., 273, 81
Lindley, D., 1979, M.N.R.A.S., 188, 159
Lindley, D., 1985, Ap.J., 294, 1
Reeves, H., 1974, Ann. Rev. Astron. Astrophys., 12, 437
Rood, R.T., Bania, T.M. and Wilson T.L., 1984, Ap.J., 280, 629
Schaeffer, R., Delbourgo-Salvador, P. and Audouze, J., 1985, Nature, in press
Shaver, P. Kunth, D. and Kjär, K. (Eds), 1984, ESO workshop on Primordial Helium (ESO, Garching)
Spite, F. and Spite, M., 1982, Astron. Astrophys., 115, 357
Vidal-Madjar, A. and Gry, C., 1984, Astron. Astrophys., 138, 285
Vidal-Madjar, A., Laurent, C., Gry, C., Bruston, P., Ferlet, R. and York, D.G., 1983, Astron. Astrophys., 120, 58

Vigroux, L., Stasinska, G., and Comte, G., 1985, Astron. Astrophys. submitted
Witten, E., 1984, Phys. Rev. D30, 272
Yang, J., Turner, M.S., Steigman, G., Schramm, D.N. and Olive, K.A., 1984, Astrophys.J., 281, 493

DISCUSSION

REES: I'd like to ask for clarification of the limits on Ω. As I understand it, a spread of at least a factor of four or five is due to the uncertainty in the Hubble constant squared. So how can you have only a factor of five spread altogether?

AUDOUZE: That's why I was questioning my value.

STEIGMAN: The uncertainty in the microwave background temperature increases the spread to a factor of five or six.

AUDOUZE: Our chemical evolution models give $\eta < 3$, which gives $\Omega < 0.06$ if we want to have good agreement with the He and D abundances.

ALCOCK: I just want to point out that if quark nuggets existed then they could have had a powerful effect on nucleosynthesis. If you form these lumps and they then evaporate, most of your baryons are condensed into very high-density regions. So at the epoch of nucleosynthesis the photon-to-baryon ratio where the baryons are is much lower than the mean photon-to-baryon ratio in the Universe. That is probably how the signature of strange matter on nucleosynthesis came about.

DAVIS: Do you include that?

AUDOUZE: No, because we did our computation ignoring the evaporation of the nuggets. If we include the evaporation of the nuggets, it does not work, because too many neutrons are released in the evaporation and we get too much D and ^{4}He. In fact, we get more ^{4}He than H.

MADSEN: The calculation of He synthesis with strange nuggets by Riisager and myself assumes that nuggets survive to the era of nucleosynthesis. In that case we find a lower limit to the baryon number of nuggets of order $A > 10^{20}\ \Omega_s{}^3$. This limit of course disappears if nuggets evaporate before that, as suggested by Alcock and Farhi.

AUDOUZE: The calculations concerning the four light elements (D, ^{3}He, ^{4}He and ^{7}Li) performed by R. Schaeffer, P. Delbourgo-Salvador and myself are in fair agreement with your conclusions given the uncertainties in the interaction between nuggets and nucleons.

FABER: I'm a little confused as to why your lower limit on Ω_b is smaller than that derived by other people.

AUDOUZE: There are two reasons. First, we took a low ^{4}He abundance - 23% - and second, we assume that we have a lot of deuterium at the very beginning.

FABER: Could you not have used ^{3}He + D to estimate the primordial D abundance?

AUDOUZE: If you want to make $^3He + D$ consistent with ^4He, you need to have a fairly low value of η if you want to have a value of the $^4He/H$ ratio of 23 - 24%.

STEIGMAN: I believe that that answer to Sandy Faber's question is correct. Audouze's constraint on $^3He + D$ is different from ours because he uses these models of infall and chemical evolution to permit him to have more $^3He + D$ than we've estimated from the destruction of ^3He. And that's the contradiction: we believe that there is an upper limit on $^3He + D$ which is violated in these models where Audouze has a factor of 15 destruction of deuterium.

FABER: Is it possible in your deuterium destruction models to significantly affect $^3He + D$ as well?

AUDOUZE: Producing too much ^3He kills the model, of course.

STEIGMAN: It is unfortunate that our knowledge of the abundances important for cosmology comes largely from our own local swimming hole, from the Solar System and the local interstellar medium. In writing the review article with Ann Boesgaard, I was impressed by the fact that if you make a plot (which I've never seen made before) of the column density of H <u>versus</u> that of D from local interstellar medium data, the H column density has a range of three orders of magnitude but correlates linearly with D with deviations of less than a factor of two. In the past I've seen D/H plotted as a ratio <u>versus</u> distance, and then the scatter looks large. Now I think that the deviation in the deuterium abundance is remarkably small, with $D/H \simeq 2\times10^{-5}$.

AUDOUZE: Yes, but as I said, maybe the deuterium abundance is not much of a problem. Maybe the problem comes from infall.

STEIGMAN: We are in perfect agreement that if the ^4He abundance is determined to some level of confidence to be 23% or less, the standard model is in serious trouble.

J. BAHCALL: If you believe despite the neutrino problem that we understand the Sun, then the lower limit on $^4He/H$ from standard models is 0.235. That is, if you take the standard model of the Sun and vary every uncertainty, as we've tried to do in looking at the problem with the solar neutrinos, you find $^4He/H = 0.245 \pm 0.01$.

AUDOUZE: But you know that the Sun is not made of primordial material. So something could have happened between the beginning and the formation of the Sun.

STEIGMAN: The helium abundance in the Sun worries me a bit because of this upper limit of 25%. Why doesn't the Sun have a solar helium abundance? The interstellar medium has a helium abundance of 28 -32 % measured in HII regions. Is the Sun discrepant, or are the uncertainties larger than people have claimed?