CHAPTER II

THE ORIGIN AND ABUNDANCES OF THE LIGHT ELEMENTS

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ON THE ORIGIN OF THE LIGHT ELEMENTS (D, ^{3}He, ^{4}He AND ^{7}Li)

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ABSTRACT. The abundances of the very light elements (D, ^{3}He, ^{4}He and ^{7}Li) constitute indeed one of the most powerful constraints in cosmology : they are known to fix very interesting limits on the baryonic density of the Universe and on the maximum number of neutrino (lepton) families in the frame of the simplest canonical models. Given the importance of these predictions, these models should be analysed very cautiously at the light of recent developments in the observations of these elements. In order to make the simplest models consistent with the observations, it is argued that a thorough destruction of D should occur during the galactic evolution. Moreover this review deals also with some models invoking the possible existence of massive unstable neutrinos, gravitinos or photinos which would decay into high energy photons or of quark nuggets which could be created during the quark–hadron phase transitions. Such models have been designed in an attempt to overcome the limitation on the Universe density coming from these abundance determinations. Although the simple canonical models are especially attractive such models cannot be disregarded .

1. INTRODUCTION

It is known since quite a long time (see e.g. Peebles 1966, Wagoner *et al.* 1967, Wagoner 1969 and 1973, Reeves *et al.*, 1973) that the lightest elements D, ^{3}He, ^{4}He and ^{7}Li are likely to be formed during the very early phases of the Universe i.e. about 100 sec after the Big Bang. It is fair to say that the nucleosynthesis of these elements constitutes an argument in favour of this cosmology theory as important as the recession of galaxies and the discovery of the 2.7 K background radiation. A very large number of papers (see e.g. the most recent reviews of Boesgaaard and Steigman, 1985 and Audouze 1987) recall that the simplest (canonical) Big Bang models seem to account for the observed abundances of these elements if the present baryonic density of the Universe ρ_B is such that the baryonic cosmological parameters ρ_B ~0.1

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(corresponding to a open Universe if there is no others significant constituent in the Universe). Moreover such models would predict the existence of a limited number (3 or 4) of different families of neutrinos (leptons) consistent with the three lepton families predicted by Grand Unification Theories GUT.

Given the importance of what can be inferred from the observed abundances of these elements, this symposium devoted to observational cosmology is indeed the place where the recent developments concerning that type of research should be analyzed. Section 2 contains a discussion of the observations relevant to these elements and their resulting primordial abundances. Section 3 summarizes the consequences on the baryonic density and the maximum number of neutrinos deduced from the simple (canonical) Big Bang models. From the current observations of D and ^{4}He especially it seems that primordial D should be largely destroyed during the Galaxy evolution. This cannot be achieved by the simplest galactic models such as those used and analyzed e.g. by Audouze and Tinsley (1974). Section 4 presents a brief account of the chemical evolution proposals which are currently made to lead to such D destruction. ^{7}Li which should (could) originate from many different astrophysical sources is also an interesting species for such evolutionary studies. Finally some of the possibilities offered by recent developments in particle physics are also considered presently in an attempt to overcome the limitation on the total density of the Universe are briefly presented in section 5. Since the bulk of the material which has been presented at Beijing has been published elsewhere, I will mainly concentrate on the latest developments and refer the reader to the list of references such as the two reviews quoted above.

2. THE "PRIMORDIAL" ABUNDANCES OF THE VERY LIGHT ELEMENTS

Let us consider in turn the four nuclear species D, ^{3}He, ^{4}He and ^{7}Li concerned by the primordial nucleosynthesis.

2.1 Deuterium

The most recent and thorough review concerning the abundance determinations of that isotope is due to Vidal–Madjar (1987) which provides an exhaustive list of references relative to this problem. This author points out the extreme variability on very short scales (down to a few parsecs) of the D/H abundances deduced from far UV observations of the nearby interstellar medium. From them he deduces that in our vicinity the "average" D/H $\sim$ $(1 \pm 0.3)\ 10^{-5}$ (following in particular the reanalysis of the Copernicus data performed by Gry *et al.* (1984). Concerning the Solar System D/H value, the best estimate remains that proposed by Geiss and Reeves (1972) from solar wind $^3He/^4He$ determinations : (D/H) solar system = $2 \pm 1\ 10^{-5}$.

A most exciting new information comes from the work of Carswell *et al.* (1987) who analyzed the higher order Lyman lines of a metal line absorption system at Z=3.08571 in the quasar Q0420–388. This system has a metallicity $Z=0.2\ Z_\odot$ (where $Z_\odot$ is the solar metallicity). These authors argue that it is in principle possible to measure a D/H ratio in such systems where the column H density N(H) $\sim 10^{18}$ cm^{-2} and where the velocity dispersion $\Delta v \leq$ 20 km s^{-1}. In that specific case they determine $\log[n(DI)/n(HI)]=-4.43^{+0.45}_{-0.26}$ which leads to $\frac{D}{H} \sim (4^{+4}_{-2.5})\ 10^{-5}$. They do not exclude entirely a possible confusion of this D determination with a low H density with high velocity although such an interpretation is quite unlikely. With their work one has the first report of a D abundance determination in astrophysical sites formed just after the birth of the Universe. We will come back in Section 4 on the importance of such measurements concerning an element like D especially affected by stellar (galactic) evolution process.

2.2 Helium 3

Nothing new has appeared in the literature since the presentation of previous reviews. The interstellar $^3He/H$ abundance is very ill defined due to very large variations between the $^3He^+$ radio measurements concerning different HII regions and performed by Rood *et al.*, 1984 : the corresponding interstellar $^3He/H$ range from less than $2\ 10^{-5}$ up to $5\ 10^{-4}$. In the Solar System $\frac{^3He}{H} \sim (1.4 \pm 0.4)\ 10^{-5}$ according e.g. to Geiss and Reeves (1972) and Black (1972).

2.3 Helium 4

There is an excellent book edited by Shaver *et al.*, 1983 which constitutes a compendium of all the abundance determinations of ^4He in any possible astrophysical site. Blue compact galaxies (BCG) appear to be the most appropriate objects to obtain the primordial abundance of ^4He (Y) ; Pagel *et al.*, 1986 have reviewed three independent accurate Y determinations due respectively to Lequeux *et al.*, 1979, Kunth and Sargent 1983 and themselves *.

* As pointed out recently by Vigroux (1986), one should be cautious not to consider together BCG results with galactic HII region ones in order to deduce $Y_{primordial}$. Any analysis mixing these two sets of determinations should be in error because of the quite different evolution behaviour of BCG and spirals.

— From Lequeux *et al.*, 1979, Y=(0.230 $\pm$ 0.004) + (3.3 $\pm$ 1.1)Z (where Z is the metallicity of BCG).

— From Kunth and Sargent, 1983, Y=(0.243 $\pm$ 0.010) + (1.4 $\pm$ 3.8)Z , but when IIZw40 is removed because of a ^{4}Helium confusion with galactic Na absorption ** their result becomes Y=(0.234 $\pm$ 0.008) + (4.6 $\pm$ 5.9)Z

— Finally Pagel *et al.*, 1986 find Y=(0.236 $\pm$ 0.005) + (5.7 $\pm$ 2.7)Z and Y= (0.238 $\pm$ 0.005) + (2.9 $\pm$ 1.5) $10^3 \frac{N}{H}$ (this last correlation between Y and the N abundance has also been noted by Vigroux *et al.*, 1986).

Depending of ones own optimism or pessimism regarding these correlations

$Y_p = (0.235 \pm 0.005) \text{or} (O.24 \pm 0.01))$.

2.4 Lithium 7

The great breakthrough regarding the primordial abundance of this element has been achieved first by Spite and Spite (1982) who showed convincingly that $(\frac{^7Li}{H})_{primordial} = 10^{-10}$ by measuring the Li abundance in a large set of halo stars (if ^{7}Li is not destroyed subsequently in the atmosphere of these stars). Subsequent works by Spite *et al.* 1984 and Spite and Spite 1986 corroborate this discovery. The fact that in their 1986 paper they report that N rich halo stars have a similar (Li/H) atmospheric abundance seems to exclude any significant mixing between the surface and the deept layers of the star and give some weight to the idea that the observed Li has not been significantly destroyed during the evolution of such stars. It is worth mentioning that the subsequent speaker Doug Duncan (who has reported on quite similar but independent observed Li abundances in pop. II metal poor stars) has argued in favour of some significantly higher primordial Li abundance such that $2\ 10^{-10} < \frac{Li}{H} < 8\ 10^{-10}$ (Duncan and Hobbs, these proceedings). Should they found to be right, the cosmological implications of such higher Li abundance are evoked in the next sections.

In order to follow the evolution of this nuclear species one should recall that $\frac{Li}{H} \sim 10^{-9}$ and $\frac{^7Li}{^6Li} \sim 12.5$ in the Solar System (see e.g. Reeves, 1974). The Li abundance has also been determined in a series of open clusters the Pleiades (Duncan and Jones, 1983) the Hyades (Cayrel *et al.*, 1984, Boesgaard and Tripico 1986), NGC 752 (Hobbs and Pilackowski 1986) and M67 (Hobbs and Pilackowski 1987). The age of these open clusters is respectively 0.1, 0.7, 1.7 and 5 10^9 years). All these measurements seem to indicate that

** D. Kunth (private communication) concurs with B.E.J. Pagel that the measurement of IIZw40 should be removed from the Kunth and Sargent, 1983, BCG sample.

$\frac{Li}{H}$ has roughly remained constant i.e. $\sim 10^{-9}$, within a factor 2, during the last 5 10^9 years (Hobbs and Pilackowski, 1987).

Another important piece of information is the isotopic $\frac{^7Li}{^6Li}$ ratio which is 12.5 in the Solar System but is significantly larger in the line of sight : 25 $< \frac{^7Li}{^6Li} <$ 150 with an average value of $\sim$ 40 (Ferlet and Dennefeld, 1984).

2.5 Summary of the available abundances of the light elements

From this review one can deduce the following table where all these determinations are assembled and listed.

TABLE 1

Abundances of the light elements D, ^{3}He, ^{4}He and ^{7}Li/^{6}Li isotopic ratio

	Primordial abundances	QSO abundances	Solar System	Interstellar medium
	t $\simeq$ 0 Gyr	t $\simeq$ 1 Gyr	t $\simeq$ 10 Gyr	t=15 Gyr
D/H (by number)	4 10^{-5}–4 10^{-4}	(2–8)* 10^{-5} *(if confirmed)	(1–3) 10^{-5}	(0.7 – 1.3) 10^{-5}
^{3}He/H (by number)	2 10^{-5}–4 10^{-5}		(1.4 $\pm$ 0.4) 10^{-5}	<2 10^{-5}–5 10^{-4}
^{4}He/H (by mass)	0.235 $\pm$ 0.005 (0) 0.24 $\pm$ 0.01 (P)		0.17–0.28	0.22–0.30
^{7}Li/H (by number)	(1 $\pm$ 0.3) 10^{-10} (S^2) (2–8) 10^{-10} (DH)		10^{-9}	(0.5–1) 10^{-9}
^{7}Li/^{6}Li			12.5	24–(40)–150

(O) : optimistic – (P) : pessimistic – (S^2) : F. and M. Spite – (DH) : Duncan and Hobbs.

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The lower limit of the Solar System Y value comes from Gautier (1983) while the interstellar Y values are extracted from various contributions published in Shaver *et al.* (1983).

The primordial D and ^{3}He values are especially uncertain because, as we will discuss it at some length in §4, they depend much on galactic evolution.

3. THE LIGHT ELEMENTS AND THE CANONICAL BIG BANG NUCLEOSYNTHESIS

The current literature contains many papers publicizing the success of the standard (canonical) model with respect to the early nucleosynthesis of D, ^{3}He, ^{4}He and ^{7}Li. Those which come to my mind are Yang *et al.* (1979 and 1984), Olive *et al.*, 1981, Boesgaard and Steigman, 1985, Steigman 1986, Steigman *et al.*, 1986, Audouze (1982, 1984, 1987, 1987) and Matzner 1986. Let me recall that the standard (canonical) model adopts the following set of hypotheses (i) the Universe was born from a very hot and dense phase (Big Bang) ensuring statistical equilibrium between the existing particles (ii) the Universe which is homogeneous and isotropic expands according the Einstein General Relativity (GR) laws where the cosmological constant Λ is equal to O. (iii) the neutron life time is equal to $\tau_{1/2} = 10.5 \pm 0.1$ minutes according to the recent analysis of Steigman *et al.*, 1987 (iv) the baryon density $\eta = n_B/n_\gamma$ (relative to that of photons) ranges between 1 to 10 10^{-10} (we will use also in the sequel $\eta_{10} = 10^{10}\eta$). One should recall at this point the relations existing between this baryon parameter η, the baryonic ρ_B density and the baryonic cosmological parameter Ω_B

$$\rho_B = 6.64\ 10^{-32}\eta_{10}(T/2.7)^3\ g\ cm^{-3} \tag{1}$$

$$\Omega_B = \rho_B/\rho_c = 3.53\ 10^{-3}\eta_{10}h^{-2}(T/2.7)^3 \tag{2}$$

where T is the temperature of the background radiation, $h = (\frac{H_o}{100})$ where H_o is the Hubble constant expressed in km s^{-1} Mpc^{-1}. v) the existing particles are non degenerate which is another way to state that the neutrino chemical potentials are negligible.

Early nucleosynthesis starts at a time short enough i.e. where the neutrons which are decaying since they are more in equilibrium with protons and leptons have still a large density but long enough in order for the temperature to be such that $10^8 < T < 3\ 10^9$ K : above such values D photodisintegrates into protons and neutrons. Therefore the current time–scale for the early nucleosynthesis is $\sim$ 100 sec.

The most critical physical parameters which govern the outcome of this nucleosynthesis are :

1– The expansion rate which can be deduced from GR and which increases with the number of boson or fermion flavors : the characteristic time of expansion is given by

$$t(s) = 2.4 g_{eff}^{-1/2} T_{MeV}^{-2} \tag{3}$$

where g_{eff} is the effective number of relativistic degrees of freedom

$$g_{eff} = \frac{43}{4}[1 + \frac{7}{43}(N_\nu - 3)] \tag{4}$$

and N_ν is the equivalent number of neutrino families

$$N_\nu = \sum_F (\frac{g_F}{2})(\frac{T_F}{T_\nu})^4 + \frac{8}{7}\sum_B (\frac{g_B}{2})(\frac{T_B}{T_\nu})^4 \tag{5}$$

In this last formula, F and B relate to the fermion and boson families which are relativistic at nucleosynthesis, T_F and T_B are their temperature relative to the neutrinos temperature T_ν. This time of expansion determines the temperature T_* at which the equilibrium between protons and neutrons freeze out, which in turn fixes the initial n/p ratio such that

$$\frac{n}{p} = \exp -(\frac{\Delta m}{T_*}) \tag{6}$$

The resulting Y is

$$\sim \frac{2n/p}{1 + n/p} \tag{7}$$

and therefore depends very much on the expansion rate : an increase of N_ν by one unit corresponds to an increase of Y by 0.01. The neutron lifetime is also a parameter which plays some role in fixing the resulting abundances of these light elements. An increase of the neutron lifetime by 0.1 mn has a quantitative effect on Y_p about ten times lower than the addition of a new neutrino family.

2 – The baryon density which determines the fusion reactions rates like those which transform D and ^{3}He into ^{4}He and ^{7}Li (^{7}Be at high densities).

The classical figure 1 extrated from Yang *et al.*, 1984 displays the resulting abundances of D, ^{3}He, ^{4}He and ^{7}Li obtained with $\tau_{1/2}$=10.6 mn and where the dependence of Y with respect to N_ν is clearly apparent.

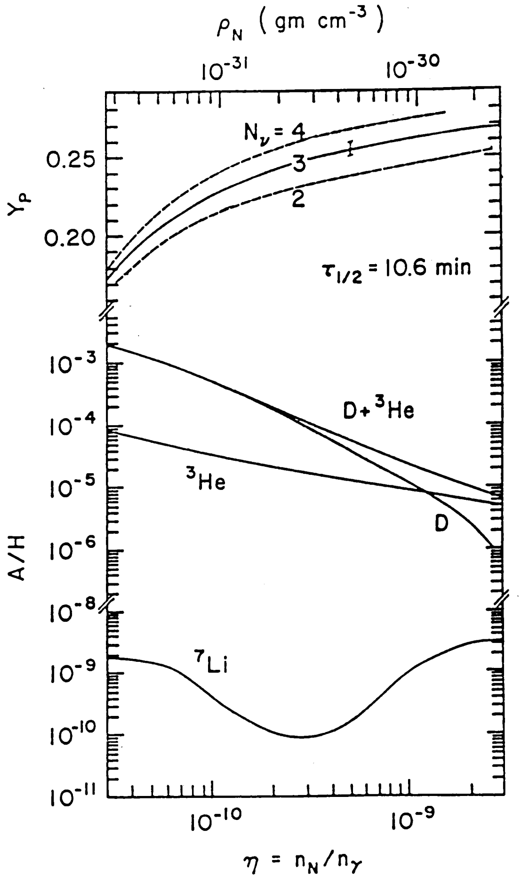

Figure 1

Resulting abundances of D, ^{3}He, ^{4}He and ^{7}Li predicted by the canonical Big Bang model against the baryon density parameter η (for a neutron lifetime $\tau_{1/2}$= 10.6 minutes). The dependence of Y (the ^{4}He abundance by mass) with N_ν the number of neutrino families is shown on this figure coming from Yang *et al.*, 1984.

By using such abundance dependences with the baryon density η, Yang *et al.*, 1984 (repeated by Boesgaard and Steigman, 1985) argue (figure 2a) that there is a range for the baryon density parameter η_{10} where an agreement can be found between the predictions coming from the four different nuclear species. According to these authors 3–4 $< \eta_{10} <$ 7–10. The upper limit comes from Y which is limited by the observations (from figure 2a one

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can see that $\eta_{10} < 10$ corresponds to Y < 0.26, $\eta_{10} < 7$ to Y< 0.254 The lower limit is constrained by the (D + ^{3}He) primordial abundance : $\eta > 3$ corresponds to (D + ^{3}He) $< 9.10^{-5}$. In this analysis they assume that D is not destroyed during the galactic evolution more than a factor 2–3 as specified by the classical models of galactic evolution such as those with infall of unprocessed material considered by Audouze and Tinsley, 1974.

From the recollection of Table 1 the alert reader realizes that now we are going to challenge somewhat this optimistic reasoning. We will not be however as extreme as e.g. Vidal–Madjar and Gry (1984) and Gautier (1983) who claim that there is absolutely no agreement between a very low η(Y) and a very high η(D) obtained in the case where D is destroyed by a modest factor during the galactic evolution.

Before doing this comparison we can make use of the instrumental relations between Y(D+^{3}He) abundances, N_ν and $\tau_{1/2}$ designed in Boesgaard and Steigman (1985) and especially in Steigman *et al.*, 1987

$$Y_p = 0.23 + 0.011 \ln \eta_{10} + 0.013(N_\nu - 3) + 0.014(\tau_{1/2} - 10.6) \qquad (8)$$

and

$$Y_p = 0.243 + 0.014[(N_\nu - 3) + (\tau_{1/2} - 10.6)] - 0.018 \log(10^4 \frac{(D +^3 He)}{H}) \quad (9)$$

From relation (7) one can draw the dependence between Y_p and $(\frac{D+^3He}{H})_p$ shown on figure 3.

For N_ν=3, Table 2 indicates the $(\frac{D+^3He}{H})_p$ calculated by Yang *et al.*, 1984 for critical values of Y (Table 1).

TABLE 2

Comparison between the primordial abundances of ^{4}He and (D+^{3}He) with N_ν=3 (from Yang *et al.*, 1984).

Y_p	(D+ ^{3}He)/H
0.25	$5\ 10^{-5}$
0.24	$1.8\ 10^{-4}$
0.235	$3\ 10^{-4}$
0.23	$4\ 10^{-4}$

For most of the values contained in this Y_p range coming from our discussion of §2 (Table 1) $\frac{D+^3He}{H} > 9\ 10^{-5}$ which is the upper limit for $\frac{D+^3He}{H}$

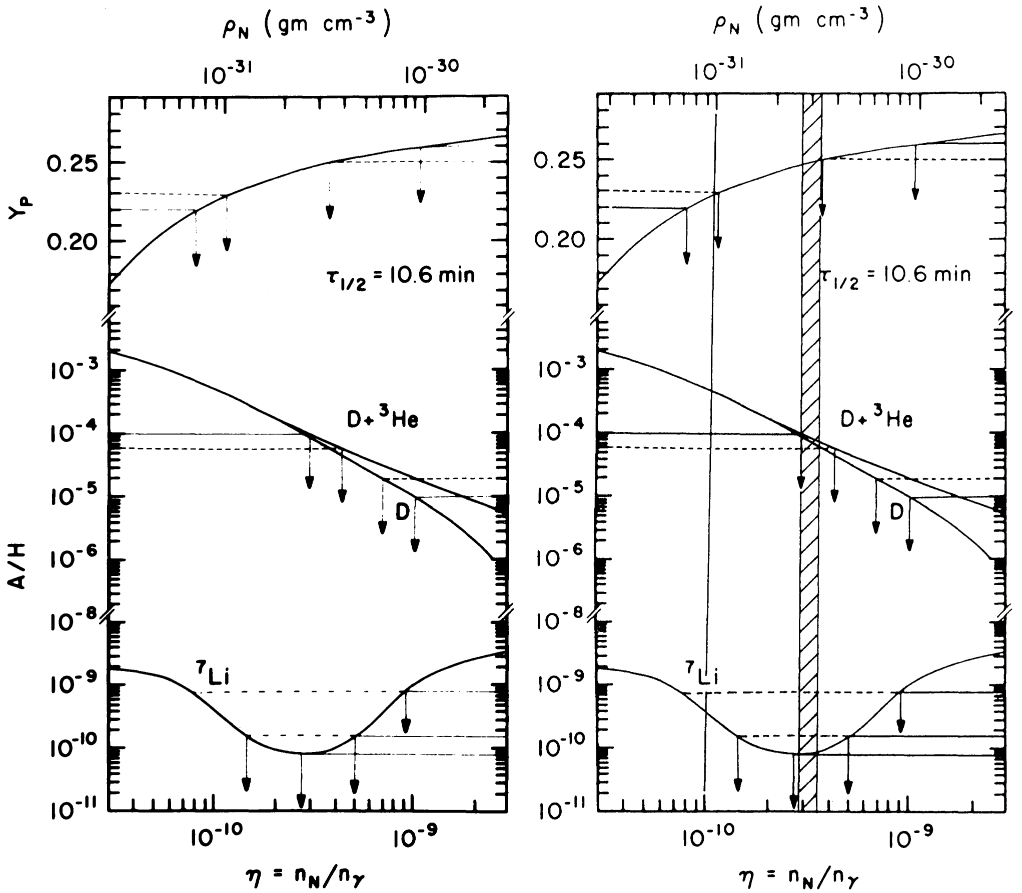

Figure 2a

Same figure as figure 1 from Yang *et al.*, 1984 for N_ν=3 and $\tau_{1/2}$=10.6 minutes. The arrows come from the "optimistic" analysis made by these authors of the ranges for the primordial abundances of the light elements which allow them to deduce $0.01 < \Omega_B < 0.14$–0.19.

Figure 2b

Same as figure 1 and 2a where I indicate the η(Y,D) range compatible both with Y_p=0.24 ± 0.01 (Kunth 1986) and with the Yang *et al.*, 1984 prescription in $\frac{D}{H} < 10^{-4}$. One sees that the resulting η range is quite narrow η=3.2±0.2 making such comparison fairly contrived. One notes also that $\frac{^7Li}{H})_p$ must be as low as the Spite and Spite (1982) prescriptions which means that population II stars cannot have destroyed their initial Li to keep this picture marginally consistent.

obtained for M. The break down to individual components is also indicated in Fig.1.

3. DISCUSSION

The spectrum observed at the galactic pole region is shown in Fig.2, where the systematic errors are included. The data of the narrow band channels are consistent with those of the wide band channels, and the component found at M can be represented by 310 ± 70 K blackbody. The isotropic component is also shown in Fig.2. The upper limit of EBL at the visible region[4] is also presented. In Fig.2 calculated EBL for two extreme cases is also shown[5]. Model 1 assumes no evolution for galaxies, while model 4 assumes that all He were synthesized in stars during early era of galaxy formation. The observed level is somewhat lower than model 4, but still considerably higher than model 1. Provided that the observed isotropic component is really extra-galactic origin, some activities at the early universe is required. Comparing our data with the recent observation of the smoothness of the sky at K[6], the fluctuation of EBL is so small that the observed isotropic radiation is hardly explained by the integrated light of the primeval galaxies. It may be worthy to mention that Carr et al.[7] predicted a similar line feature at the redshifted wavelengths for Lymann α due to the pregalactic pop. III objects.

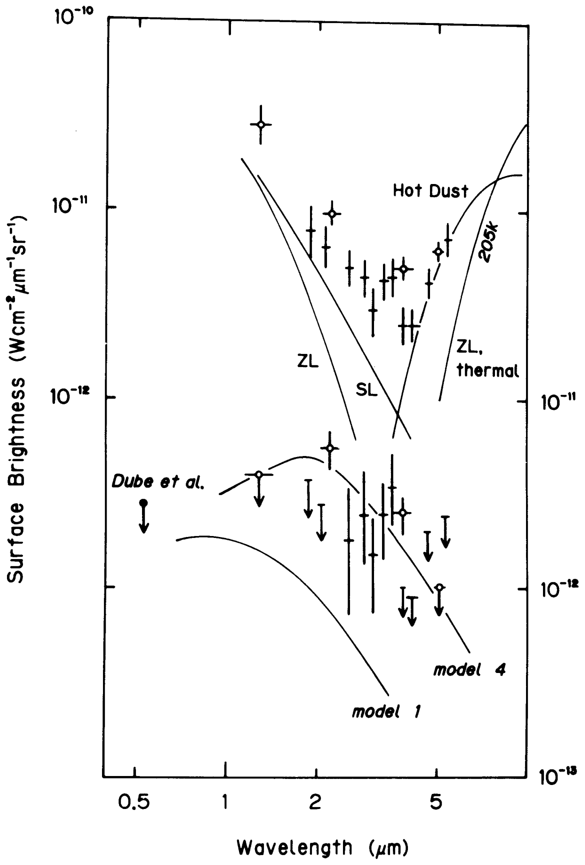

Fig.2. The spectrum of the observed surface brightness at the galactic pole region. Open circles and crosses are data of the wide and narrow band channels, respectively. The lower part shows the spectrum of the isotropic component. The unit of the surface brightness is indicated at the right side.

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$\frac{^7Li}{H} \leq 9\ 10^{-10}$), is found to be correct. This is why in our group we have found useful to analyze chemical evolution models leading to a more thorough D destruction during the galactic life without any overproduction of ^{3}He.

4. SPECIFIC MODELS OF GALACTIC EVOLUTION ALLOWING A LARGER D DESTRUCTION

For that purpose we have considered three possible scenarios (a) infall or inflow of processed (D poor) material in the considered zone (here the solar vicinity) (b) destruction of D by stellar winds released during the premain sequence phase. These two types of scenarios have been analyzed in some details by Delbourgo–Salvador *et al.*, 1985, (c) evolution models assuming bimodal star formation processes (see e.g. Gusten and Mezger 1983, Larson 1986, Wyse and Silk 1987). These models have inspired us (Audouze *et al.*, 1987) to perform some preliminary computations leading to the expected large D destruction.

I am not writing again here the classical equations of chemical evolution which can be found e.g. in Delbourgo–Salvador *et al.*, 1985. These equations become most simple in the case of Deuterium which is destroyed inside the stars. The general equation describing the classical evolution of the D abundance by mass X_D is quite simple :

$$\frac{d(\sigma X_D)}{dt} = -\nu\sigma X_D + \delta(X_D) \tag{10}$$

where σ is the gas density (relative to the total mass of galactic matter), ν the rate of astration and δ the rate of infall or inflow.

(i) In models without infall

$$X_D = (X_D)_{primordial}\ e^{-\nu t} \tag{11}$$

(ii) In models with infall of unprocessed material

$$\frac{X_D}{(X_D)_{primordial}} = \frac{1}{\sigma}(1 - \frac{\delta}{\nu})e^{-\nu t} + \frac{\delta}{\nu} \tag{12}$$

(iii) With infall (or inflow) of processed material

$$\sigma X_D = (X_D)_{primordial} e^{-\nu t} + (X_D)_{process}\frac{\delta}{\nu}(1 - e^{-\nu t}) \tag{13}$$

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(iv) In models where stellar mass loss from pre main sequence stars is taken into account (in these stars the only nucleosynthetic process which could occur is the D transformation into ^{3}He) : equation (10) is replaced by (14) :

$$\frac{d(X_D\sigma)}{dt} = -\nu(1+f)\sigma X_D + \delta(X_D)_{process} \tag{14}$$

where f is the mass fraction of premain sequence stars lost by stellar winds during these early phases. The resulting X_D abundance is

$$\frac{X_D}{(X_D)_{primordial}} = \frac{1}{\sigma}(1 - \frac{\delta}{\nu(1+f)})e^{-\nu(1+f)t} + \frac{\delta}{\nu} \tag{15}$$

In the <u>case of Helium 3</u>, classical models of stellar evolution teach us that low mass stars can release significant fractions of ^{3}He during the red giant phases. According to Iben and Truran (1978), the resulting $(\frac{^3He}{H})$ at the end of this phase is :

$$\frac{^3He}{H} = 2.6\ 10^{-4}(\frac{M}{M_\odot})^{-2} + 0.7(\frac{^3He}{H})_{init} \tag{16}$$

when one takes into the IMF the rate of ^{3}He released after that phase is $\propto K(M/M_\odot)^{-4}$. As discussed in Delbourgo–Salvador *et al.*, 1985 the rate of ^{3}He released during the Asymptotic Giant Branch is less important. Finally ^{3}He should mainly come from low mass stars (stars with m>5 $M_\odot$ should not eject any ^{3}He which is itself destroyed inside such stars.

The general equation describing the ^{3}He abundance by mass X_3 evolution is

$$\frac{d(\sigma X_3)}{dt} = -\nu\sigma X_3 + \int_{m_L}^{m_u} E_3(M)\phi(M)\nu\sigma(t-\tau_m)dM + \delta X_3(\mathrm{inf}) + \nu f\sigma X_D \tag{17}$$

where $E_3(M)$ is the ^{3}He fraction released from a star of mass m, τ_m being its lifetime and $\phi(M)$ the usual initial mass function IMF.

The galactic evolution of D and ^{3}He computed through equations (13), (15) and (17) in the frame of models a) and b) are shown in figures 4a, 4b and 5 coming from Delbourgo–Salvador *et al.*, 1985.

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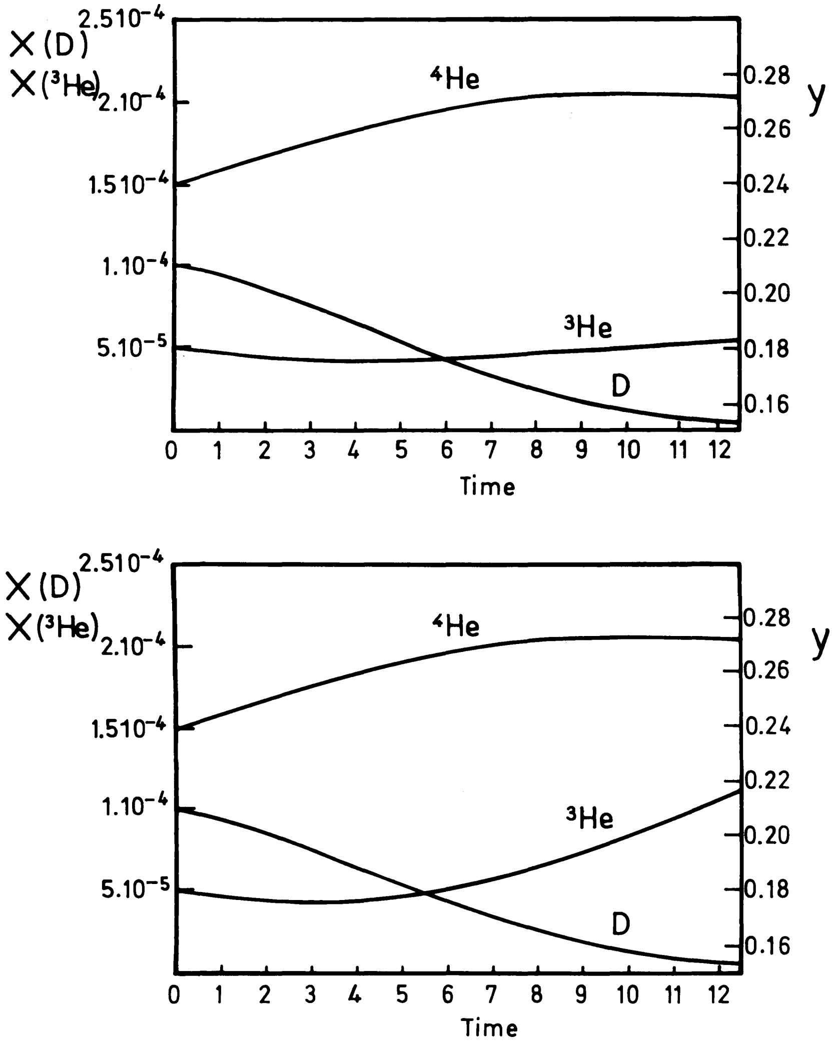

Figures 4a and 4b

Resulting abundances by mass of ^{4}He, ^{3}He and D as a function of time (in Gyr) in chemical evolution models with infall of processed material such that the ^{3}He production rate is a) 5 10^{-5} $(M/M_\odot)^{-4}$. b) 5 $10^{-4}(M/M_\odot)^{-4}$. The infall rate is δ = 0.012 with ν=0.45 (from Delbourgo–Salvador *et al.*, 1985).

These two types of models are able to account for a D destruction such that $D/D_p \sim 1/15$ sufficient to reconcile $\eta_{10}(D)$ with $\eta_{10}(^4He)$. With the prescriptions of these two types of models the baryonic density η_{10} range inside

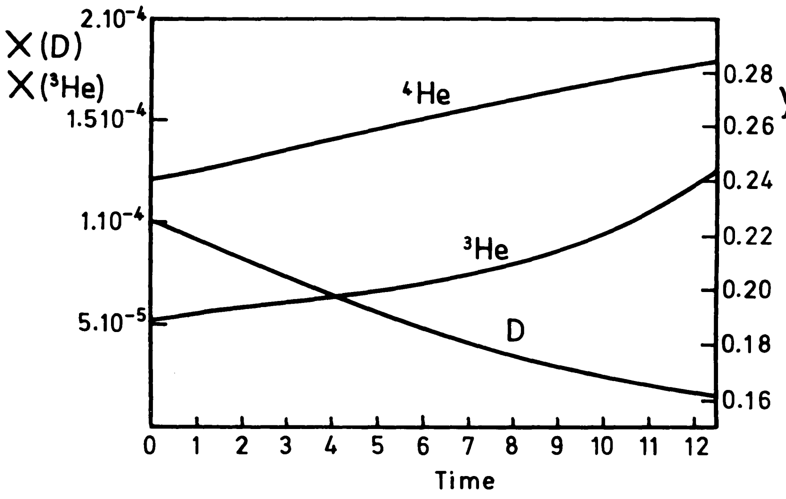

Figure 5

Abundances by mass of ^{4}He, ^{3}He and D as a function of time (in Gyr) with f=0.2 (see text). The production rate of ^{3}He is 5 10^{-4} $(M/M_\odot)^{-4}$, the infall rate δ=0 here (from Delbourgo-Salvador *et al.*, 1985).

which there is such an agreement is $1.2 < \eta_{10} < 4.5$ leading to $4\ 10^{-3} \leq \Omega_B \leq 6\ 10^{-2}$. It should be noted that this resulting Ω_B parameter is significantly lower than that proposed by Yang *et al.*, 1984.

The third type of model c) called the bimodal star formation model has been proposed and considered by several authors (see e.g. Larson 1986). The aim of such models where the rate of star formation especially those of low mass is increased to provide a viable solution for many problems like the G dwarf problem and the evolution of metallicity with time (Pagel and Patchett, 1975), an increase of the resulting M/L ratios and a better account of the colors of the solar vicinity and spiral galaxies than it is achieved in simpler and therefore more classical models. For instance, Wyse and Silk, 1987, consider a bimodal star formation model such that the massive star mode has a star formation rate (SFR) decreasing exponentially with time while the mode which contains stars of all mass has a constant SFR. By doing it these authors have constructed galactic evolution models able to account for the age metallicity relation of the thin disk and the halo. After hearing the oral presentation of my Princeton paper (Audouze, 1987), Larson (1986) noted that this type of model should lead to high (D_{prim}/D_{pres}) ratios.

In Audouze *et al.*, 1987, following a suggestion of J. Silk we have computed the D evolution in a model of that type : In this model the SFR is supposed to be constant with time scale : $\tau_{*1} \propto \nu_1$ such that ν_1=1 for times t $\leq 10^9$ years, then when t $> 10^9$ years, the SFR is exponentially decreasing with time such that the time scale $\tau_{*2} \propto \nu_2 \sigma$ where ν_2=0.3.

With such models at times t=12.5 Gyr, σ=0.04 $D_{pres}/H = 10^{-5}$, $\frac{^3He}{H} pres \sim 10^{-4}$, Y $\sim$ 0.30, Z=0.025 and $\frac{D_{prim}}{D_{pres}}$=15.

That type of model then fulfills the two requirements that we seek to reconcile any baryonic density parameter η, i.e. a large D destruction and a not too large present $^3He/H$ abundance.

The merit of these galactic models is that they can be proved or disproved by three different ways (i) one could expect an improvement of the radio search of interstellar $^3He^+$ abundance as currently pursued by R.T. Rood and his associates. Any viable galactic evolution cannot predict a present ^3He abundance higher than the largest ^3He measured abundances in the interstellar medium ; (ii) more determinations of the D abundances in high redshift QSOs : these models are only valid if $(\frac{D}{H})_{QSO} >$ (5-10) 10^{-5} for lower values D/H $\leq 5\ 10^{-5}$ the more classical models in which D is not as destroyed would be favoured. One notes that the present (D/H) abundance proposed by Carswell *et al.*, 1987 is quite ambiguous in that respect for the z=3.09 QSO 0420–388. (iii) the third method suggested by Delbourgo–Salvador *et al.*, 1987 is to look for any D abundance variation between different galactic sites where the gas density can vary. Remember that

$\sigma < 0.01$ in central region of our galaxy while

$\sigma \sim 0.05$ in the solar vicinity.

If, for simplicity one uses a model with the constant recycling approximation, the gas density is given by

$$\frac{d\sigma}{dt} = -\nu\sigma(1-\alpha) + \delta \tag{18}$$

with $\alpha \simeq 0.2$ being the integrated mass fraction coming back from stars to ISM. From (18) it is easy to show that the relation between the infall (inflow) rate and the astration rate depends significantly on σ_{pres} (the present gas density) :

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$$\delta = \nu(1-\alpha)\frac{\sigma_{pres} - \exp(-\nu(1-\alpha)t_{pres})}{1 - \exp(-\nu(1-\alpha)t_{pres})} \tag{19}$$

In the case of inflow of processed material,

$$\frac{(X_D)_{prim}}{(X_D)_{pres}} = \frac{\delta}{\nu(1-\alpha)}e^{\nu t} + (1 - \frac{\delta}{\nu(1-\alpha)})e^{\alpha\nu t} \tag{20}$$

and if D is destroyed during the stellar premain sequence phase

$$\frac{(X_D)_{prim}}{(X_D)_{pres}} = e^{\nu t(\alpha+f)} \tag{21}$$

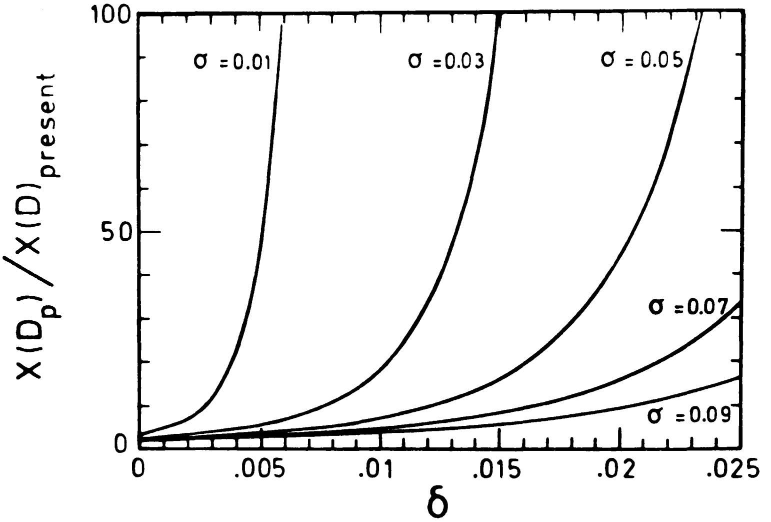
Figures 6a and 6b show how the resulting $(X_D)_{prim}/(X_D)_{pres}$ ratios are much dependent on σ_{pres} for these two types of model.

Future work will then tell us who is right between those like us who favor large D destruction during the galactic history or those like Yang *et al.*, 1984 who trust the classical galactic evolution models leading to moderate D destructions.

Before closing this section devoted to the interplay between galactic evolution models and the early nucleosynthesis, I would like to make the following remark regarding ^{7}Li. The present debate between those like Spite and Spite (1982) who argue in favour of a primordial ^{7}Li/H abundance as low as $\sim 10^{-10}$ and Duncan and Hobbs (1987) for whom $(^7\mathrm{Li/H})_{prim} > 2\ 10^{-10}$ has the following consequences : in favour of the Spite and Spite (1982) view is the fact that one deduce from it a η_{10} (^{7}Li) value consistent with η(D) and η(Y) but one has to explain why ^{7}Li has increased dramatically during the first billion years of galactic evolution and remain constant afterwards as pointed out by Hobbs and Pilackowski (1987). If $(\mathrm{Li/H})_p$ is higher, then one has difficulty to reconcile the resulting η(Li) with η(D) and η(Y) and if one does so, one is led to very low $\Omega_B \ll 0.01$. On the other hand the chemical evolution of ^{7}Li in that case is far easier to be explained. We (i.e. J. Silk, E. Vangioni–Flam, R. Wyse and myself) are currently investigating this problem in the Spite and Spite (1982) terms within the frame of bimodal star formation which should lead to a rapid Li increase at the beginning of the galactic history <u>if</u> the ^{7}Li production is related to <u>massive stars</u>.

5. EARLY NUCLEOSYNTHESIS AND PARTICLE PHYSICS

The simple (canonical) Big Bang models with specific galactic evolution hypotheses if one follows the french school or without if one trusts the Chicago–Ohio–Minesotta group seems to imply that the number of neutrino (lepton)



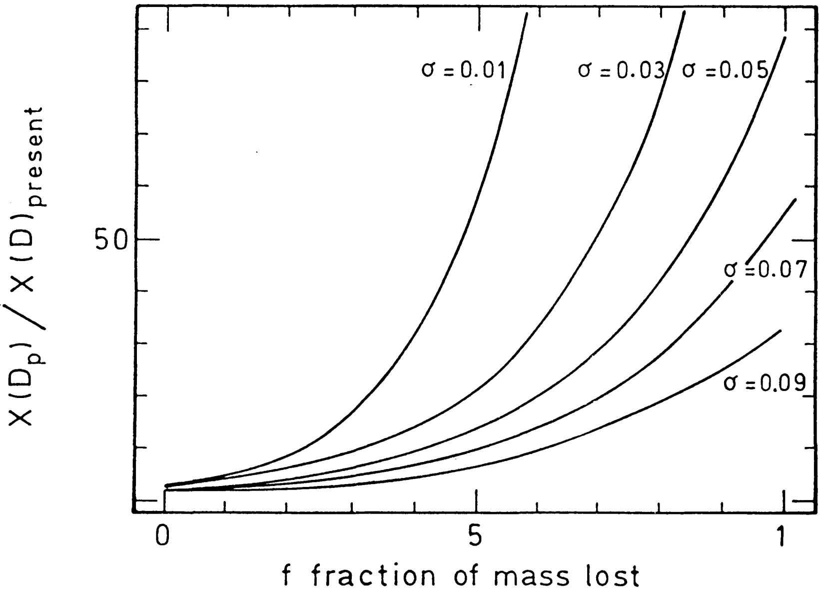


Figure 6a

Relation between the ratio $X(D)_{prim}/X(D)_{pres}$ and the rate of infall δ for different values of the present gas density σ ranging from 0.01 to 0.09 (from Delbourgo–Salvador *et al.*, 1987).

Figure 6b

Relation between the ratio $X(D)_{prim}/X(D)_{pres}$ and the fraction of mass f lost during the pre main sequence phase for different values of the present gas density σ ranging from 0.01 to 0.09 (from Delbourgo–Salvador *et al.*, 1987).

families is limited to the three already known species (in agreement with GUT theories) and that the baryonic cosmological parameter $\Omega_B \sim 0.1$. In this section, I would like to make a brief account of some models based on recent particle physics developments which have been built in order to see if the light element abundances resulting from the Big Bang can be consistent with $\Omega=1$ values. These high Ω values have been found to be a consequence of current inflationary models. There are two ways to achieve that goal (i) either Ω_B is large, then the Big Bang nucleosynthesis would result in ^{4}He and ^{7}Li overabundances and D and ^{3}He underabundances ; *. these discrepancies with respect to the observed "primordial" abundances can be solved if photodisintegration processes triggered by high energy photons coming from the decay of massive particles destroy in part ^{4}He and ^{7}Li and restore the D and ^{3}He observed abundances from them. This type has been considered e.g. by Audouze *et al.*, 1985 who analyzed such processes occuring after the decay of massive neutrinos and gravitinos while Salati *et al.*, 1987 conducted a similar analysis with decaying photinos (ii) the other alternative is to have Ω large because of the existence of non baryonic particles which act as mere spectators of the early nucleosynthesis : the literature and these proceedings contain many different proposals advocating in favour of hot dark matter (neutrinos with mass of 50 eV ...) or of cold dark matter (axions, strings ...). In our work we have considered only stable photinos (Salati *et al.*, 1987) or stable quark nuggets (Schaeffer *et al.*, 1985). We will summarize only here the few points which deserve to be made on that question.

5.1 Early photodisintegration processes affecting the light element abundances

Three possibilities have been considered up to now although any other massive decaying particle able to produce high energy gamma rays with the appropriate time scale is fitted for this specific purpose. There are (i) massive neutrinos with masses of $\sim$ 500 MeV and life–time $\sim 10^5$–10^6 sec ; (ii)

* After the Beijing conference I became acquainted with the proposal currently made by Applegate *et al.*, 1987 according whom the quark–hadron phase–transition which should be a first order phenomenon could lead to huge inhomogeneities of proton and especially neutron distribution : neutrons are especially favoured in the evolution of such Big Bang plasmas because their diffusion mean free path is much larger than that of protons. With such a proposal interesting, nucleosynthetic byproducts can be synthetized not only the very light elements under consideration here but also heavier elements. In their so–called segregated model, this new type of early nucleosynthesis could be consistent with the D, ^{3}He, ^{4}He and ^{7}Li primordial values for an Ωh^2 value of 1 which is the main aim of the models described here.

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are (i) massive neutrinos with masses of $\sim$ 500 MeV and life–time $\sim 10^5$–10^6 sec ; (ii) gravitinos, the 3/2 spin particles which are the supersymmetric (SUSY) counterparts of the 2 spin gravitons. Their mass range from 20 GeV and 1 TeV and their lifetime is $\sim 10^5$–10^6 sec ; these two first possibilities have been considered by Audouze *et al.*, 1985 and (iii) unstable photinos of comparable lifetime (Salati *et al.*, 1987).

Lindley (1985) has shown very convincingly why these particles should have a lifetime as long as 10^5–10^6 sec. The physical reason is the following : there exists an energy threshold E_γ for these gamma rays such that

$$E_\gamma kT = \frac{1}{50} MeV^2 \tag{22}$$

where kT is the thermal energy of the Universe background radiation.

Above this threshold, the high energy photons scatter on the thermal photons and produce (e^+ e^-) pairs while below the threshold they can Compton scatter on electron, induce (e^+ e^-) pair production by scattering on the nuclei or induce photofission. The energy E_γ of the photofission gamma rays should be high enough to be above the photofission reaction threshold i.e. $E_\gamma > 20$ MeV. On the other hand $E_\gamma kT < \frac{1}{50}$ MeV^2 for this photofission to take place : For $E_\gamma > 20$ MeV, $kT < 10^{-3}$ MeV, $t \geq 10^5$–10^6 sec. Therefore photofission processes cannot occur at times shorter than these 10^5–10^6 sec during which the light elements are protected against photofission by (e^+ e^-) pair production.

The minimum energy for the gamma rays to induce photofission and the conditions on the time scale define a fairly precise set of decay life–time–mass conditions for these particles. As examples Figure 7 extracted from Audouze *et al.*, 1985, shows how part of ^{4}He can be transformed into D and ^{3}He by high energy gamma rays coming from the decay of gravitinos. Figure 8 from Salati *et al.*, 1987 is a map of the lifetime–mass of decaying photinos defining 5 different regions for a Universe such that Ω=0.02.

In region I the photinos are not massive enough to induce any photofission : they only act as another neutrino family and lead therefore to an overproduction of ^{4}He. Region II corresponds to photinos with a lifetime too short to affect the nucleosynthesis. In region III D is dissociated , in Region IV all three elements D, ^{3}He and ^{4}He are dissociated while in region V a partial photodisintegration of ^{4}He leads to an overproduction of ^{3}He. The results of the early nucleosynthesis can then constrain significantly the mass–lifetime relation for unstable photinos and have interesting predictions on the physics of the different possible decay models of photinos (see Salati *et al.*, 1987 for more details).

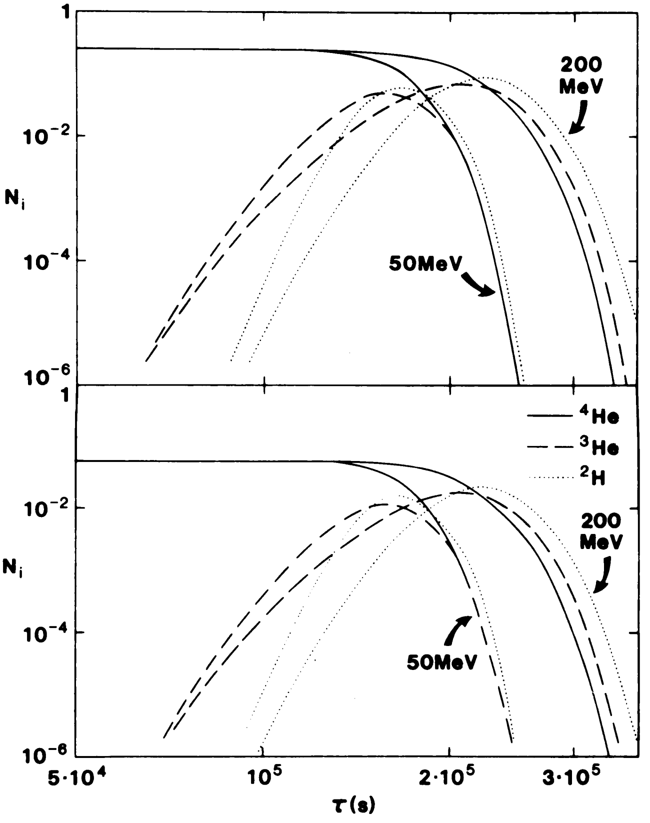

Figure 7
Effects of decaying gravitinos on light element abundances : Y_p=1 for the upper panel and Y_p=0.24 for the lower one ; $X_p(D)=X_p(^3He)=0$. The two sets of curves have been calculated for 50 MeV and 200 MeV electrons (respectively 100 MeV and 400 MeV photons), τ_s is the gravitino lifetime (from Audouze *et al.*, 1985).

To sum up any massive $\geq$ 500 MeV long lived ($\tau \geq 10^5$–10^6 sec) particle decaying in high energy gamma rays can affect the outcome of early nucleosynthesis by photofission reactions.

5.2. Early nucleosynthesis in the presence of particles acting as spectators

We have envisaged so far two possible types of particles which are non baryonic, which could act as spectators of the early nucleosynthesis and induce large cosmological parameter value Ω=1. The first possibility is stable photinos of mass in the fairly narrow range $3 \leq M_{\tilde{\gamma}} \leq 8$ GeV which could close the Universe and still be consistent with the primordial abundances

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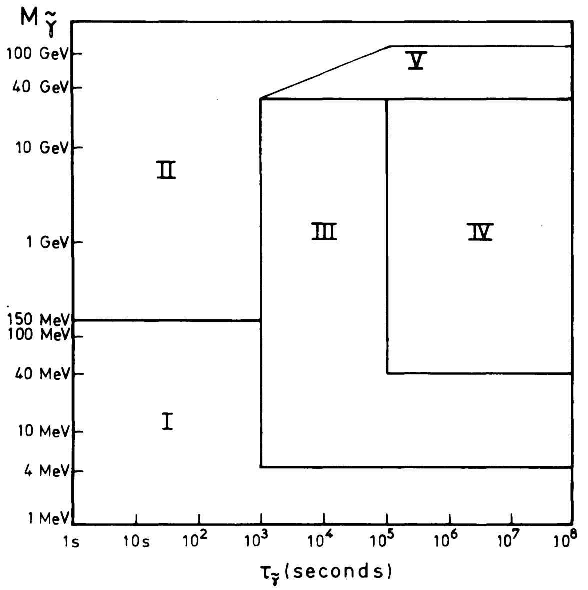

Figure 8
Photino mass ($M_{\tilde{\gamma}}$) and lifetime ($\tau_{\tilde{\gamma}}$) domains defined by the nucleosynthesis constraints for Ω=1. Each domain is defined in the text. The only allowed domain is region I (low lifetime – high mass) and the border of this region with domain III (from Salati *et al.*, 1987).

of the light elements (Salati *et al.*, 1987). The second possibility are quark nuggets. This term designates particles with atomic mass $10^2 < A < 10^{57}$ and $Z \sim 5\ A^{1/3}$ made up of 3 A quarks (u, s and d quarks in equal amounts) and which would fill up the "nuclear desert" between the heaviest nuclei and the neutron stars (de Rujula, 1986). These quark nuggets could have been produced during the quark–hadron transition (Witten, 1984). Schaeffer *et al.*, 1985 have suggested that an $\Omega \geq 1$ Universe can be consistent with the results of the early nucleosynthesis if such nuggets exist, if they are stable and if they have an appropriate atomic mass : $10^{15} < A < 10^{17}$. This A range may have to be changed after a better account of the nuclear absorption and emission rates from these nuggets. However one should remind that Alcock and Fahri, 1985 claim that quark nuggets of any atomic mass disappear by transforming themselves into nucleons before the time of nucleosynthesis.

In short it is not impossible to build up models with low Ω_B and large Ω coming from some specific types of particles like stable photinos and quark nuggets but it may not be the most likely hypothesis.

6. CONCLUSION

To sum up the discussion presented above, the very light elements D, ^{3}He, ^{4}He and ^{7}Li remain still very powerful and handy cosmological tools.

1 – Regarding the observations, one can expect in a foreseable future significant progress on several important issues :
— determination of D abundances both in various galactic locations (where the relative gas densities are different from each other) and in the absorption line systems of quasars at high redshifts. Such observations should allow to distinguish between the galactic evolution model preferred in our group (see e.g. Delbourgo–Salvador *et al.*, 1987) which lead to a huge D destruction during the galactic history and therefore large variations of D with the considered galactic locations and significantly large D abundances in high redshifts QSOs. If such variations are not found, one should come back to the views expressed by the Chicago group (see e.g. Yang *et al.*, 1984). In this case, one may have some difficulty to reconcile the baryon densities predicted by ^{4}He and D primordial abundances respectively.

— determination of ^{3}He abundances : we anticipate forthcoming exciting data on the interstellar ^{3}He abundances coming from R.T. Rood and his associates. A significant decrease of the interstellar ^{3}He concerning especially the high value found for the W3 HII region would be most useful in constraining effectively the rate of ^{3}He formation and therefore of D destruction during the galactic evolution.

— after the discussions concerning the ^{4}He abundance determinations in blue compact galaxies (Pagel *et al.* 1986, Kunth 1986, Shields private communication) one might expect to know soon Y_p with an accuracy of 5 %.

— after the works of different groups pionnered by F. and M. Spite and their associates and followed by those of Duncan and Hobbs, Boesgaard *et al.*, one should have soon a clear–out view on the primordial abundance of ^{7}Li.

I have argued here that the standard (simple or canonical) Big Bang model still stands very well to account for the "observed" primordial abundances of the very light elements if D is largely destroyed during the galactic evolution. In that respect new and successful galactic evolution models like the bimodal star formation model of Larson, 1986 considered also by Wyse and Silk (1987) are especially suited to achieve that type of D behaviour. In that case as noted by Delbourgo–Salvador *et al.*, 1985, the resulting Ω_b would be somewhat smaller than the value quoted e.g. by Boesgaard and Steigman (1985) $4\ 10^{-3} < \Omega_b < 6\ 10^{-2}$ instead of $0.01 < \Omega_B < 0.14$. In this situation the Universe should be filled by large density of non baryonic particles in order to account for the dynamics of its large scale structures.

I have also considered also models derived from recent developments in particle physics. Most of them have been designed in our group, but see also Scherrer and Turner, 1987, like those of Audouze *et al.*, 1985, or of Salati *et al.*, 1987 which take advantage of the possible existence of massive, long lived particles like massive neutrinos, gravitinos or photinos which could decay in releasing high energy photons able to partially photodisintegrate ^{4}He and ^{7}Li produced in a large Ω_B universe (the dark matter would be baryons in that case). Other models like Schaeffer *et al.*, 1985 attempt to take advantage of the possible existence of quark nuggets which are nuclearites which could appear during the quark–hadron phase transition (Witten, 1984) and assist like spectators to the early nucleosynthesis while filling the Universe with their mass. In that respect it is interesting to mention the recent proposal of Applegate *et al.* (1987) who take advantage of the possible existence of large baryon density fluctuations which could occur in the QCD or electroweak phase transition and lead to the formation of very neutron rich regions which in turn would trigger some interesting processes pertaining to primordial nucleosynthesis.

Although these problems have not been evoked in this presentation, interesting works have still to be pursued in three directions. a) study of models with non zero cosmological constant Λ which should be the signature of fast expanding Universes, b) study of models where the chemical potential of neutrinos can be high and then pursue the discussion initiated by David and Reeves, 1980 and by Steigman, 1985, c) analysis of models corresponding to inhomogeneous and/or anisotropic Universes and pursue the work of e.g. Rothman and Matzner (1984), Delbourgo–Salvador (1986) and Matzner (1986).

Because of the many progresses achieved both in the observation of faint far and/or old objects in the overall geometry of the Universe, in the understanding of particle physics and in the construction of new unification schemes, one expects that the formation of the very light elements (D, ^{3}He, ^{4}He and ^{7}Li) will inspire for sometime exciting new ideas which may be useful to cosmology.

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DISCUSSION

PECKER: 1) The He^4 may not be as "primaeval" as you think it should be, if diffusion of H vs. He, under the influence of radiation pressur acting on H-Lyα, but not on He Lyα or HeII-Lyα, is acting in objects where a large number of ionizing photons ionize H and He locally. In other terms, loss of H may be a way to see an apparent enhancement of He abundance.

2) About the Sourian baryonic-symmetry model, based on distribution of quasars. Do you mean you do not accept his statistical analysis of such a distribution?

AUDOUZE: 1) There are ample discussions among the specialists about ionization effects on He in blue compact galaxies. In a sample of about 100 objects, only 10 of them which show sufficiently ionization effects were kept in order to avoid any improper correction. Their method seems very safe in that respect.

2) About symmetric models. I do not believe that the Sourian models belong to the class I am criticizing, in which the amount of matter is equal to that of antimatter. The only thing I said is that the relative number of photons relative to baryon prevents equality between matter and antimatter densities.

NORMAN: As we heard this morning, we may well need a significant value for the cosmological constant. What will this do to your standard model. For example, will this change your limit on the number of neutrinos. Possibly the extra push in expansion due to λ will then reduce the allowed number of ν's to below three. An interesting way to look at this, perhaps, is to use the ^{4}He abundance and $N_\nu = 3$ to limit the cosmological constant.

AUDOUZE: I should say that both the Chicago and the Paris groups have not yet investigated properly models with non-zero cosmological constant. My bet is that you are right in saying that the ^{4}He abundance puts a strong limit to near zero values for this constant. For non-zero values the expansion is accelerated and would lead to much too high He abundance. Therefore the limits that we could put on this constant should be quite stringent and close to zero.

NARLIKAR: If we assume that Y_p lies in the range 0.24 ± 0.01, how do we account for very low values of Y ($\lesssim 0.20$) in certain objects?

AUDOUZE: At present the only real difficulty would come from the Jupiter atmosphere observations. Some chemical fractionation could affect the He/H ratio deduced from this site. But it is true that if $Y < 0.22$ the simple Big Bang model is in trouble.

BURKE: Recently Kardashev has proposed that the baryon asymmetry that we observe locally is a fluctuation of finite extent in a larger universe with a mean baryonic density of zero. What implication would this have for your model?

AUDOUZE: The simple early nucleosynthesis model works only with specific expansion in rates and baryonic density contents. I am not aware of the Kardashev model. I can only say that in order to explain the light element abundances in the frame of our hypothesis any model should come with the same type of expansion and baryonic density content. To pursue this question, I have heard in informal conversations that Dr. Hogan is developing some models in which he would predict the appropriate amount of ^{4}He in models emphasizing the role of the quark-hadrun first order transition.

SETTI: A couple of years ago it was said that primordial nucleosynthesis models would constrain the number of neutron types to no more than 4-5. What has changed now to bring the limit down to 3?

AUDOUZE: It is the noticeable decrease of the He abundance quoted by Pagel (1986) and independently supported by Kunth (1986) which makes me feel that $N_\nu = 3$ is the actual limit to the number of neutrino families. This conclusion would also be reinforced with higher primordial Li abundances as suggested by Duncan (this conference).

SILK: The Chicago models of primordial nucleosynthesis allowance of Ω_M require baryonic dark matter, but your standard models (at least some of them) do not. Could you comment on the origin of this difference?

AUDOUZE: The main difference between the Chicago school models and ours comes from the galactic evolution of D (and possibly also of ^{3}He): we presently favour significant decreases of D by factors of about 10 during the galaxy history which would lead to large ($\sim 10^{-4}$) primordial D abundance in agreement with the primordial ^{4}He abundance (and also larger ^{7}Li abundances). This would lead to lower values of η (Ω) such that $4 \times 10^{-3} \leq \Omega \leq 0.06$ which would limit in a more stringent way the baryonic dark matter present in the Universe. As said in the talk, there is an observational test (the D abundance/interstellar gas density correlation) which should support (rule out) our models relative to theirs.

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