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Proceedings of Japan-France Seminar on Chemical Evolution of Galaxies

Early Nucleosynthesis

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After a brief summary of our present knowledge of the primordial abundances of the very light elements (D, ^{3}He, ^{4}He and ^{7}Li), the simplest model of primordial nucleosynthesis is presented. Its implications on the baryonic density of the Universe and the number of neutrino (lepton) families are outlined. Recent models dealing with specific scenarios of chemical evolution of our Galaxy and with the possible presence of non baryonic particles (massive neutrinos, gravitinos, photinos, quark nuggets ...) are also discussed.

Keywords: Nucleosynthesis, nuclear astrophysics, chemical evolution of galaxies, cosmology, observational astronomy.

Introduction

This french–japanese seminar devoted on galactic evolution and stellar formation has started by the outstanding presentation of Professor Katsuhiko Sato about "the Universe at its very beginning ($t <$ 1sec)". He convinced us that the introduction of the cosmological constant Λ by A. Einstein is highly benefitial to cosmology. Before hearing Professor Saturo Ikeuchi reviewing for us the formation of galaxies and large structures which took place at the end of the radiative era i.e. at times $\gg 10^6$ years, it is worth to consider what happened at times $\sim$ 100 sec, when the lightest elements D, ^{3}He, ^{4}He and ^{7}Li have been formed as by-products of the very high temperature–density conditions which existed then. It is well known that the early nucleosynthesis is one of most solid arguments in favour of the occurence of the Big Bang. In the foundation of that cosmological theory, it plays a role as important as the recession of galaxies pointed out by Hubble and the discovery of the 2.7 K background radiation by Penzias and Wilson. The further consequence of this early nucleosynthesis is that it leads to most useful limits on the baryonic density of the Universe such that the corresponding cosmological parameter $\Omega_b \sim 0.1$ (which would mean that the Universe is "open" and would expand for ever if there is no other form of matter than baryons). Moreover it implies a maximum number of neutrino (lepton) families of 3 to 4 consistent with the three lepton families which appear in the Grand Unification Theories. These most important implications are made in the frame of the so-called simple or canonical Big Bang model. The purpose of this presentation is threefold : a) I summaryze our knowledge on the primordial abundances of D, ^{3}He, ^{4}He and ^{7}Li (section 2) ; b) I discuss the implications of the simple (canonical) models. As it will be discussed in section 3, the D and ^{3}He abundances are much affected by the chemical evolution of galaxies ; I will attempt to convince the reader that a thorough destruction of D during the galactic history is almost mandatory to reconcile the predictions on the present baryonic density of the Universe coming from ^{4}He and D respectively. This shows also that this contribution, which must discuss the various models of chemical evolution able to account for such a large D destruction, fits in the general framework of this seminar devoted to galactic evolution ; c) I will end up this contribution by mentioning briefly some of the attempts made in our group to alleviate the constraint on the overall density of the Universe. We invoke in particular the existence of still hypothetical particles like massive neutrinos, gravitinos, photinos, quark nuggets ... in order to try to reconcile a possible "closed" (bouncing) Universe with the results of the primordial nucleosynthesis (section 4). Similar work which is done in Japan along these lines will also be mentioned.

Since this type of review has been published already in several occasions (ref. 1, 2, 3), I will present only here a very brief outlook of the main points mentioned above.

2. The primordial abundances of the very light elements D, ^{3}He, ^{4}He and ^{7}Li

Reference 3 contains an updated review of the determination of the primordial abundances of these very light elements. Table 1 summarizes and lists such primordial abundances. The very large uncertainties on the primordial abundances of D and ^{3}He are due to the fact that D is very easily transformed into ^{3}He at relatively modest temperatures (T > 10^5 K) in stellar interiors. Therefore the D and ^{3}He abundances depend much on the ways by which the interstellar medium evolves into stars.

Table 1. Abundances of the light elements D, ^{3}He, ^{4}He and ^{7}Li/^{6}Li isotopic ratios
( ) numbers correspond to the bibliographic references.

	Primordial abundance	QSO & Pop. II stars abundances	Solar System	Nearby interstellar medium
time (Gyr)	0	~ 1	~ 10	15
D/H	$4\ 10^{-5}$–$4\ 10^{-4}$	$(4^{+4}_{-2}\ 10^{-5})^*$(4) if confirmed	$(2 \pm 1)\ 10^{-5}$(5)	$(1 \pm 0.3)\ 10^{-5}$(6)
^{3}He/H	$2\ 10^{-5}$–$4\ 10^{-5}$		$(1.4 \pm 0.4) 10^{-5}$(5)	$<2\ 10^{-5}$–$5\ 10^{-4}$ (7)
Y (^{4}He/H by mass)	0.24 ± 0.01 (8) 0.235 ± 0.005 (optimistic view from 16)		0.17–0.28 (10) (11)	0.22–0.30 (11)
^{7}Li/H	$(1 \pm 0.3)\ 10^{-10}$ (12) $(2$–$8)\ 10^{-10}$ (13)	$(1 \pm 0.3)\ 10^{-10}$ (12,13)	10^{-9} (14)	$(0.5$–$1)\ 10^{-9}$ (17)
^{7}Li/^{6}Li			12.5 (14)	25–150 ($\sim$ 40) (15)

3. The light elements and the standard Big Bang nucleosynthesis in the frame of recent models of galactic evolution

In the standard Big Bang nucleosynthesis the following assumptions are made : (i) The Universe was born from a very dense and hot phase (Big Bang) leading to a statistical equilibrium between the existing particles (ii) the Universe is homogeneous and isotropic and its expansion is governed by General Relativity (GR) with a cosmological constant $\Lambda=0$ * (iii) the Universe is asymmetric (the matter density is much higher than that of antimatter) and the baryon density parameter $\eta_{10} = 10^{10}\ n_B/n_\gamma$ lies between 1 and 10. Let me remind to the reader that the present baryonic density in the Universe ρ_B=6.64 $10^{-32}\ \eta_{10}\ (T/2.7)^3$ g cm^{-3} (T being the actual temperature of the background radiation, while the baryonic cosmological parameter $\Omega_B = \rho_B/\rho_c$ (ρ_c being the critical density) $\Omega_B = 3.5\ 10^{-3}\ \eta_{10}\ h^{-2}\ (T/2.7)^3$ with h = (Ho/100) with Ho being the Hubble constant expressed in km s^{-1} Mpc^{-1} (iv) The leptons are not degenerate and the chemical potential of neutrinos is very small.

The two crucial parameters which govern the outcome of that early nucleosynthesis are : (i) the rate of expansion of the Universe which in turn is related to the number of neutrino flavours : when this number increases the total density of the Universe becomes higher from GR, the expansion time scale becomes shorter which means that the temperature at which neutrons and protons are no more in equilibrium (the freeze out temperature) T_* increases. This results in an increase of the $(\frac{n}{p})_{freezing}$ ratio given by

$$(\frac{n}{p})_{freezing} \propto \exp(\frac{-\Delta m}{T_*})$$

where Δm is the mass difference between proton and neutron. Since the resulting primordial abundance (by mass) $Y_p \sim 2\ \frac{n}{p}/1 + \frac{n}{p}$, the addition of new neutrino flavours results in larger Y_p. In simple words, the addtion of 1 new neutrino family increases Y_p by ≈ 0.01 see e.g. fig. 1 extracted from Yang *et al.* (ref. 16). (ii) The rates of the nuclear reactions which take place after the n–p absorption reaction leading the D formation at $T \lesssim 10^9$ K are proportional to the baryonic density. The resulting primordial abundance of D, ^{3}He and ^{7}Li are very sensitive to this parameter : as it is known for a long time (see e.g. ref. 17), the D primordial abundance fixes an upper limit to the

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* Should Λ be > 0 during the time of nucleosynthesis the expansion would be more rapid inducing a larger production of ^{4}He which seems to be infirmed by the present observations. If $\Lambda \neq 0$ as suggested by Prof. H. Sato, it should be at earlier periods.

present density of the Universe such that $\Omega_B < 0.1$–0.2. If there is no other massive component in the Universe this low value of the cosmological parameter corresponds to an open Universe. Fig. 1 shows the classical dependence of the primordial abundance of the light elements with the baryon density parameter η drawn by Yang *et al.* (ref. 16). Taken like it is, the primordial nucleosynthesis fixes quite interesting constraints on the baryonic density of the Universe and the maximum number of neutrino flavours 3 or 4 which corresponds to the present determination of three different leptons (e, μ and τ), to the SU(5) group of the Grand Unification Theory and to the maximum number of light neutrinos ($\sim$ 4) deduced from the CERN determinations of the energy width of the Z^0 boson.

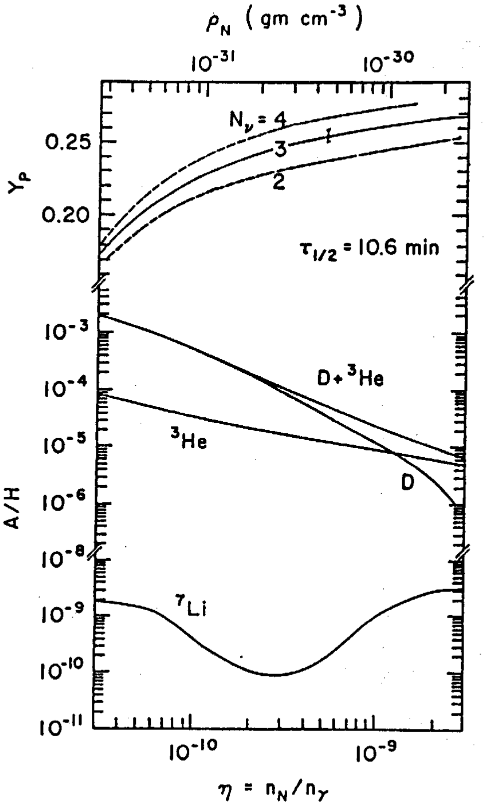
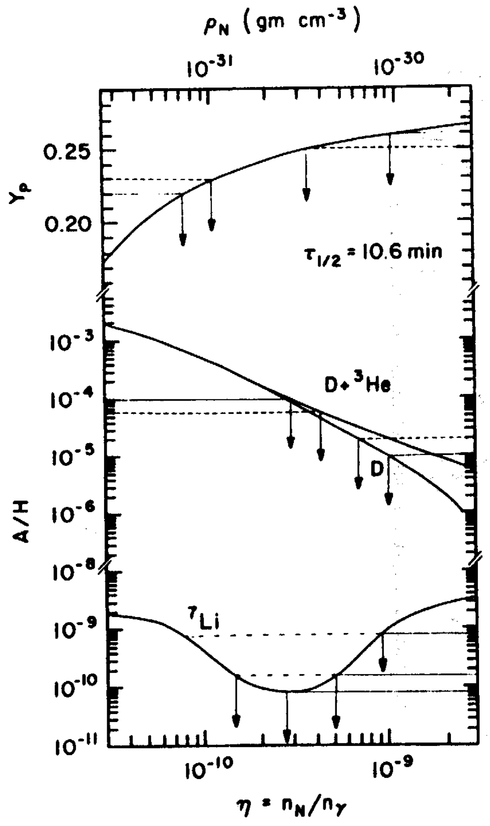


Figure 1

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.*, Ref. 16.

There is a great difference of interpretation between the american school and our group. Yang *et al.* (ref. 16) advocate that there is a fairly large range of baryon density parameters (figure 2a) satisfying together the prescriptions coming from the primordial abundances of (D + ^{3}He), ^{4}He and ^{7}Li. For these authors $4 < \eta_{10} < 7$ and $0.012 < \Omega < 0.14$. For our group, see e.g. ref. 3, there is not such a striking agreement when the new Y_p determinations (ref. 8) is taken into account even when one adopts the view that $(D + {}^3He)/H < 10^{-4}$ as Yang *et al.* (ref. 16) (fig. 2b) one deduces that in this case $\eta_{10}=3.2 \pm 0.2$ corresponding to $0.01 \leq \Omega \leq 0.04$ depending on the choice of Ho (a similar conclusion was already pointed out by Pagel, ref. 18). It should be stressed at this point that there is not such marginal agreement if $({}^7Li/H)_{primordial}$ is found to be $({}^7Li/H)_p \geq 2\ 10^{-10}$ as suggested in (ref. 13).



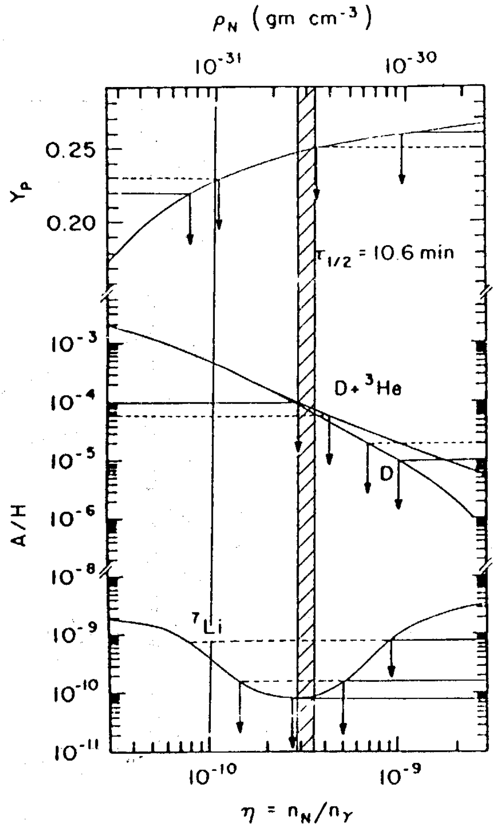
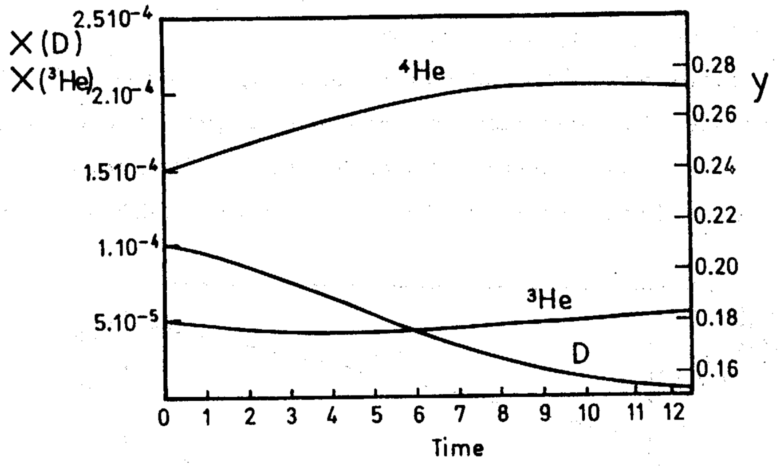
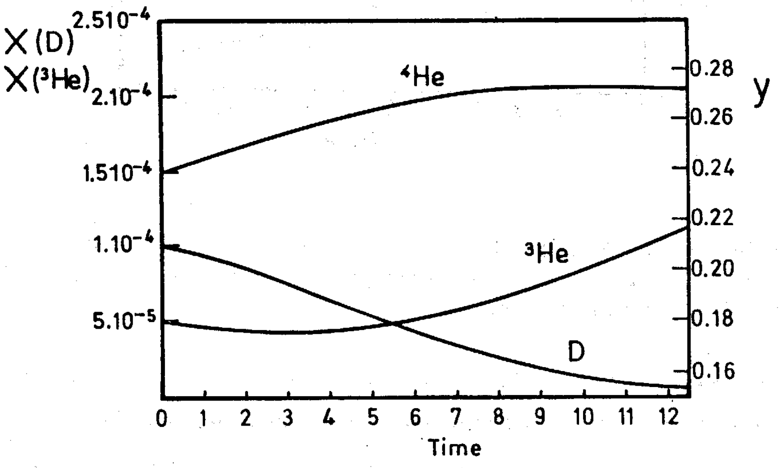


Figure 2a Same figure as figure 1 from ref. 16 for $N_\nu=3$ and $\tau_{1/2}=10.6$ minutes. The arrows come from the "optimistic" analysis made by these authors of the ranges for the primordial abundances of the light elements which allow them to deduce $0.01 < \Omega_B <$ 0.14–0.19.

Figure 2b
Same as figure 1 and 2a where I indicate the η(Y,D) range compatible both with $Y_p=0.24 \pm 0.01$ (Kunth, ref. 8) and with the Yang *et al.*, ref. 16, prescription in $\frac{D}{H} < 10^{-4}$. One sees that the resulting η range is quite narrow $\eta=3.2\pm0.2$ making such comparison fairly contrived. One notes also that $\frac{{}^7Li}{H})_p$ must be as low as the Spite and Spite (ref. 12) prescriptions which means that population II stars cannot have destroyed their initial Li to keep this picture marginally consistent.

In order to solve this difficulty we (ref. 19) have proposed that D should be thoroughly destroyed during the galactic history meaning that $(D/H)_p$ should be $\geq 10^{-4}$ and that the model of galactic evolution should differ from classical ones (ref. 20). In ref. (19) one can find the description of two different models of galactic evolution leading to thorough D destruction while avoiding to overproduce ^{3}He. They are (i) infall or inflow of already processed material : computations corresponding to that case are shown on figure 3a and 3b, (ii) mass loss suffered by pre main





Figures 3a and 3b
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) $5\ 10^{-6}$ $(M/M_\odot)^{-4}$. b) $5\ 10^{-4}(M/M_\odot)^{-4}$. The infall rate is $\delta = 0.012$ with ν=0.45 (from Delbourgo-Salvador *et al.*, ref. 19) with ν the astration rate equal to 0.45. Both δ and ν are expressed in units of 10^9 years (from ref. 19).

sequence stars able to transform D into ^{3}He (fig. 4). Both models lead to $D_{primordial}/D_{present} \sim$ 15. From them Delbourgo-Salvador *et al.* (ref. 19) deduce that $1.2 < \eta < 4.5$ corresponding to $4\ 10^{-3} < \Omega_b < 0.06$ (significantly lower that the Ω_B deduced by Yang *et al.*, ref. 16). A third possibility based upon galactic models with bimodal star formation rate (as suggested by Larson, ref. 21) leads to similar conclusions (see e.g. Audouze *et al.*, ref 22).

There are at least three ways to test that hypothesis of a large D destruction during the galactic history :

1) to see if forthcoming measurements of the interstellar ^{3}He abundances will be able to restrict the present uncertainties regarding this abundance.

2) to have more measurements of D/H abundances in absorption systems of QSO of large redshifts since the possible D/H determination of Carswell *et al.* (ref. 4) is very ambiguous, either $(D/H)_{QSO} > 5\ 10^{-5}$ and would support such models with large D destruction or $(D/H)_{QSO} < 5\ 10^{-5}$ and then we would be forced to come back to the classical models of ref. 20.

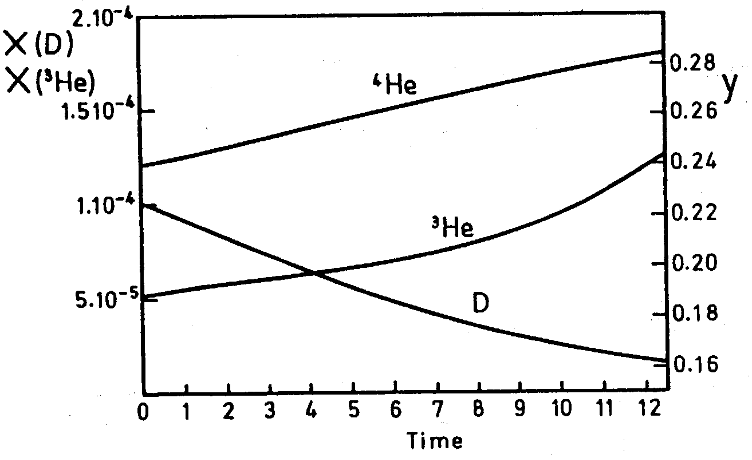


Figure 4
Abundances by mass of ^{4}He, ^{3}He, D as a function of time (in Gyr) with $f = 0.2$ (20 % of the mass of a star lost during the premain sequence phase). The production rate of ^{3}He is $5\ 10^{-4}$ $(M/M_\odot)^{-4}$. There is no infall (from ref. 19).

3) A third test has been proposed by Delbourgo-Salvador *et al.*, (ref. 23) who shows that the present (D/H) abundance should vary significantly with the present gas density in the case of large D destruction over the galactic history. This can be tested by far UV space experiments able to measure D/H in various locations of the galactic disk where the gas densities are different and be an excellent project for a collaboration between french and japanese specialists in UV astronomy.

To sum up this discussion, the standard (canonical) model seems still to be the most appealing and bring many exciting constraints on the maximum baryon density of the Universe (such that $\Omega_B < 0.1$) on the maximum number of neutrino flavours ($N_\nu \sim 3$) and possibly also on the galactic evolution models (the main theme of this seminar). In that respect the comparison between the ideal D primordial abundance and the present ones might be another argument in favour of models with bimodal star formation.

4. Early nucleosynthesis and particle physics

It is pleasing to note that the interaction between particle physics and early nucleosynthesis is a subject interesting both the group of Professor K. Sato and my own and where forthcoming collaborative efforts could take place. The aim pursued in such studies is to examine if Big Bang models with $\Omega = 1$ (corresponding to inflationary Universes) can nevertheless be consistent with the observed abundances of the very light elements. In models where one takes specifically into account the possible existence of new classes of particles in an attempt to answer this question one can distinguish two possible situations. In the first one Ω_B remains as low as ~ 0.1 and the Universe would be filled with non baryonic matter acting like mere spectators of the primordial nucleosynthesis. In the second one $\Omega_B \sim 1$ which would lead to significant overabundances of ^{4}He and ^{7}Li and underabundances of D and ^{3}He. One can then imagine that at very early epochs massive unstable particles were able to release high energy photons which could photofission in part ^{4}He and ^{7}Li and restore the observed D and ^{3}He abundances. In the first class of hypotheses : non baryonic particles spectators of the early nucleosynthesis, Schaeffer *et al.* (ref. 24) have suggested that stable massive quark nuggets made of 3 A (u, s and d) quarks which could be created during the quark–hadron transition could be considered as possible candidate for such a role. However one should recall here that Alcock and Fahri (ref. 25) are arguing that such nuggets cannot survive at the time where early nucleosynthesis takes place. Another candidate would be stable photinos (the existence of which is predicted by supersymmetry theories as reviewed e.g. by Fayet, ref. 26) with masses comprised between 3 and 8 Gev (ref. 27).

The second class of models invokes the existence of massive unstable particles which could decay into high energy photons. As shown by Lindley (ref. 28) the effects induced by these high energy photons depend on their energy E_γ and that of the thermal photons kT : i) if $E_\gamma.kT > 1/50$ MeV^2 these high energy photons scatter on electrons and produce ($e^+ e^-$) pairs : it is only when E_γ kT $< 1/50$ MeV^2 that energetic photons are able (in principle) to photofission nuclei. Since the threshold for such photofission reactions is > 20 Mev kT$\ll 10^{-3}$ MeV which means that t$\geq 10^5$-10^6 sec. One then is limited to consider massive particles with life time $\geq 10^5$–10^6 sec. Three possible candidates have been envisaged : gravitinos (the spin 3/2 supersymmetric partner of the spin 2 gravitons) (ref. 29). As an example, Figure 5 taken from this work shows how gravitinos with masses from 20 Gev to 1 TeV are able to account for the recovering of the observed abundances of D and ^{3}He from ^{4}He if their life time is $\geq 10^5$ sec. Massive neutrinos of comparable life time have also been considered in that perspective by Audouze *et al.* (ref. 29) and Kawasaki *et al.* (ref. 30). The photofission induced by unstable photinos has been studied in some detail (in ref. 27). This analysis has been used to put interesting constraints on the physical properties of such particles. Figure 6 can be used as a guide to summarize this analysis. Region I correspons to photinos unable to induce photofission because they are too light but the existence of which would induce an overabundance of ^{4}He because they would act as another neutrino family. In Region III, D is dissociated while in Region IV all light nuclei are dissociated, in Region V ^{4}He would be partially dissociated into ^{3}He which would become then underabundant.

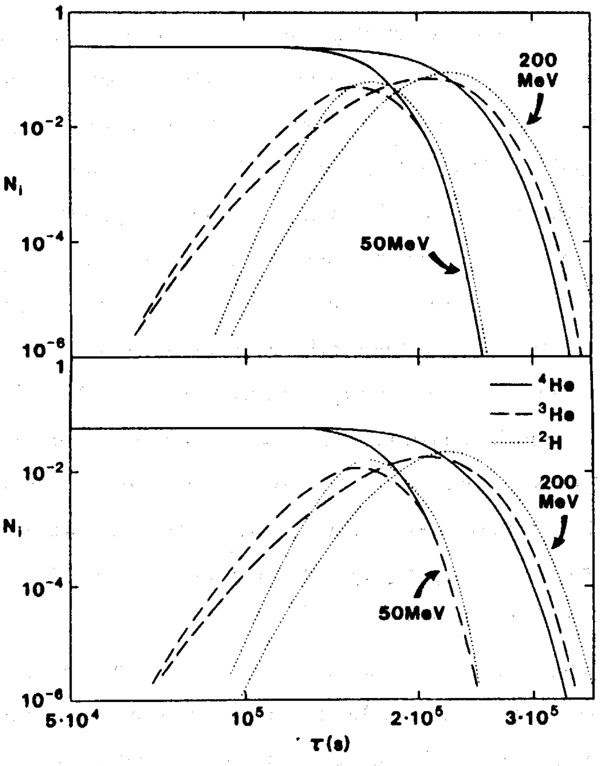


Figure 5

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_g is the gravitino lifetime (from Audouze *et al.*, ref. 29).

The only region consistent with the observed abundances of the light elements would be region II and the bordering part of region III i.e. massive photinos with low lifetime. As shown in much more detail (in ref. 27) these conditions may be compared with those coming from the particle physics itself to put quite exciting constraints on the mass, life time, decay mode of the photinos which could be subject to future experimental verification. As a possible example one can see on figure 7 (from ref. 27) how early nucleosynthesis can constrain the possible relation between the mass of the photino and the supersymmetric breaking scale $\sqrt{d}$. As said at the beginning of this section, collaboration between japanese and french astrophysicists could be initiated on such exciting problems at the frontier of cosmology, astrophysics and particle physics.

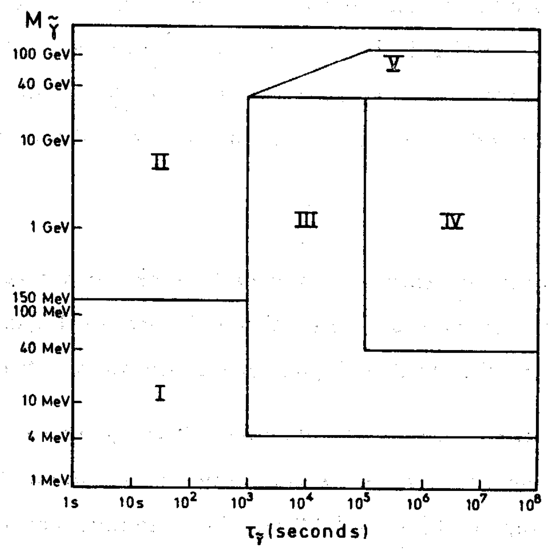


Figure 6

Photino mass ($M_{\tilde\gamma}$) and lifetime ($\tau_{\tilde\gamma}$) domains defined by the nucleosynthesis constraints for $\Omega=1$. 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.*, ref. 27).

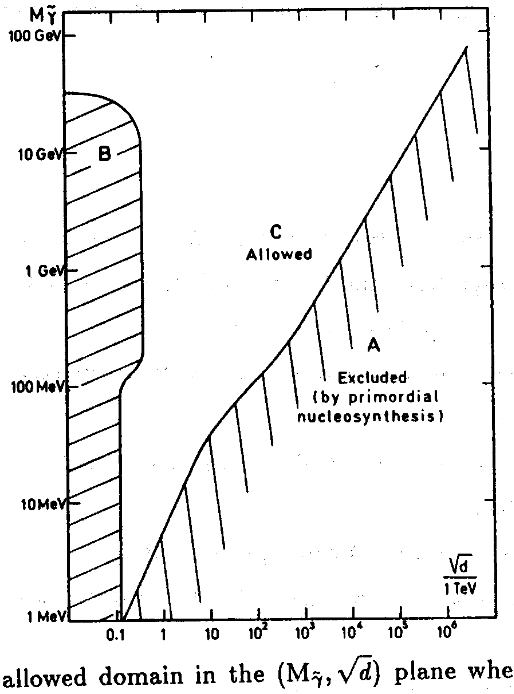


Figure 7

Definition of the allowed domain in the ($M_{\tilde\gamma}, \sqrt{d}$) plane where $M_{\tilde\gamma}$ is the mass of unstable photinos and $\sqrt{d}$ is the supersymmetric breaking scale expressed in TeV. Both by nucleosynthesis constraints which exclude domain A (low $M_{\tilde\gamma}$ and high $\sqrt{d}$) and by particle physics which excludes domain B (high $M_{\tilde\gamma}$ and low $\sqrt{d}$). Only domain C is allowed (from ref. 27).

5. Conclusion

In the frame of this short contribution I have been unable to develop at length the many exciting problems related to the formation of the very light elements just after the Big Bang : there is much observational work to be done to refine knowledge on the abundances of these very light elements. Chemical evolution of galaxies is a topic which interests both the french and the japanese community and which has very strong ties to that domain. Finally the relation between particle physics, nuclear physics and cosmology should inspire many studies in our two countries.

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References

1) Boesgaard A.M. and Steigman G., 1985, Ann. Rev. Astron. Astrophys. , **23**, 319

2) Audouze J., 1987, in Nucleosynthesis and Chemical Evolution of Galaxies, eds B. Hauck and A. Maeder, Saas-Fee proceedings, in press.

3) Audouze J., 1987, in Observational Cosmology, eds. G.R. Burbidge, A. Hewitt and L.Z. Fang, Reidel-Dordrecht, in press

4) Carsweel R.F., Irwin M.J., Webb J.K., Baldwin J.A., Atwood B., Robertson J.G. and Shaver P.A., 1987, to be published

5) Geiss J. and Reeves H., 1972, Astron. Astrophys., **18**, 126

6) Vidal-Madjar A., 1987, in Space Astronomy and Solar System Exploration, ed. W.R. Burke, ESA-SP 268

7) Rood R.T., Bania T.M. and Wilson T.L., 1984, Ap. J., **280**, 629

8) Kunth D., 1986, P.A.S.P., in press

9) Pagel B.E.J., Terlevich R., Melnick J., 1986, Pub. Astr. Soc. Pacific, in press

10) Gautier D., 1983, in Primordial helium, P.A. Shaver *et al.* eds, ESO Garching, p. 139

11) Shaver P.A., Kunth D., and Kjär K. eds., 1983, Primordial helium, ESO-Garching publication

12) Spite F. and Spite M., 1982, Astron. Astrophys., **115**, 357

13) Duncan D.K. and Hobbs L.M., in Observational Cosmology, eds. G.R. Burbidge, A. Hewitt and L.Z. Fang, Reidel-Dordrecht to be published

14) Reeves H., 1974, Ann. Rev. Astron. Astrophys., **12**, 437

15) Ferlet R. and Dennefeld M., 1984, Astron. Astrophys., **138**, 303

16) Yang J., Turner M.S., Steigman G., Schramm D.N. and Olive K.A., 1984, Ap. J., **281**, 493

17) Reeves H., Audouze J., Fowler W.A. and Schramm D.N., 1972, Ap. J. **179**, 909

18) Pagel B.E.J., 1986, in Material Content of the Universe, publication of the Royal Astron. Soc.

19) Delbourgo-Salvador p., Gry C., Malinie G. and Audouze J., 1985, Astron. Astrophys.,**150**, 53

20) Audouze J. and Tinsley B.M., 1974, Ap. J., **192**, 487

21) Larson R.B., 1986, M.N.R.A.S., **218**, 409

22) Audouze J., Delbourgo-Salvador P. and Vangioni-Flam E., 1987, in Advances in Nuclear Astrophysics, eds. J. Audouze, M. Cassé, J.P. Chièze and E. Vangioni-Flam, editions Frontières, to be published

23) Delbourgo-Salvador P., Audouze J. and Vidal-Madjar A., 1987, Astron. Astrophys., in press

24) Schaeffer R., Delbourgo-Salvador P. and Audouze J., 1985, Nature, **317**, 6036

25) Alcock C. and Fahri E., 1985, Phys. Rev. D, **32**, 1273

26) Fayet P., 1984, in Large scale structure of the universe, cosmology and fundamental physics, G. Setti and L. Van Hove eds., p.35

27) Salati P., Delbourgo-Salvador J. and Audouze J., 1987, Astron. Astrophys., in press

28) Lindley D., 1985, Ap. J., **294**, 1

29) Audouze J., Lindley D and Silk J., 1985, Ap. J. Letters, **293**, L53

30) Kawasaki M., Terasawa N. and Sato K., 1987, M.N.R.A.S, in press