

# Big bang nucleosynthesis updated with the NACRE compilation

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**Abstract.** We update the Big Bang Nucleosynthesis calculations on the basis of the recent NACRE compilation of reaction rates. The average values of the calculated abundances of light nuclei do not differ significantly from those obtained using the previous Fowler's compilation. However,  ${}^7\text{Li}$  is slightly depressed at high baryon to photon ratio  $\eta$ . Concerning  ${}^{10}\text{B}$ , its abundance is significantly lower than the one calculated with the Caughlan & Fowler (1988) rates as anticipated by Rauscher & Raimann (1997). We estimate the uncertainties related to the nuclear reaction rates on the abundances of  $D$ ,  ${}^3\text{He}$ ,  ${}^4\text{He}$ ,  ${}^6\text{Li}$ ,  ${}^7\text{Li}$ ,  ${}^9\text{Be}$ ,  ${}^{10}\text{B}$  and  ${}^{11}\text{B}$  of cosmological and astrophysical interest. The main uncertainty concerns the  $D(p, \gamma){}^3\text{He}$  reaction rate affecting the synthesis of  ${}^7\text{Li}$  at rather high baryonic density and also the  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  and  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  reactions. On the left part of the lithium valley the uncertainty is reduced due to the improvement of the measurement of the  $T(\alpha, \gamma){}^7\text{Li}$  reaction rate. The observed abundances of the nuclei of interest are compared to the predictions of the BBN model, taking into account both observational and theoretical uncertainties. Indeed, the  ${}^7\text{Li}$  abundance observed in halo stars (Spite plateau) is now determined with high precision since the thickness of this plateau appears, in the light of recent observations, exceptionally small ( $< 0.05$  dex). The potential destruction/dilution of  ${}^7\text{Li}$  in the outer layers of halo stars which could mask the true value of the primordial abundance is in full debate, but the present trend is towards a drastic reduction of the depletion factor (about 0.10 dex). It is why we use this isotope as a preferred baryometer. Even though much efforts have been devoted to the determination of deuterium in absorbing clouds in the line of sight of remote quasars, the statistics is very poor compared to the long series of lithium measurements. Taking into account these lithium constraints, two possible baryonic density ranges emerge,  $\eta_{10} = 1.5\text{--}1.9$  and  $\eta_{10} = 3.3\text{--}5.1$ . In the first case,  $\text{Li}$  is in concordance with  $D$  from Webb et al. (1997) and  ${}^4\text{He}$  from Fields & Olive (1998) and Peimbert & Peimbert (2000). In the second case, agreement is achieved with  $D$  from Tytler et al. (2000) and  ${}^4\text{He}$  from Izotov & Thuan (1998).

Concerning the less abundant light isotopes, the theoretical BBN abundance of  ${}^6\text{Li}$  is affected by a large uncertainty due to the poor knowledge of the  $D(\alpha, \gamma){}^6\text{Li}$  reaction rate. However,

at high  $\eta$ , its abundance is so low that there is little chance to determine observationally the true BBN  ${}^6\text{Li}$  abundance. But, at low  $\eta$ , its abundance being one thousandth of that of primordial  ${}^7\text{Li}$ , 6/7 ratio measurements at very low metallicity are not totally hopeless in the future. Nevertheless, in the present situation,  ${}^6\text{Li}$  is cosmologically relevant, though indirectly, since its mere presence in a few halo stars, corroborates the fact that it is essentially intact in these stars together with  ${}^7\text{Li}$  and thus the Spite plateau can be used as such to infer the primordial  ${}^7\text{Li}$  abundance. The  $\text{Be}$  and  $\text{B}$  abundances produced in the Big Bang are orders of magnitudes lower, and spallation of fast carbon and oxygen is probably their unique source, in the early Galaxy.

**Key words:** cosmology: miscellaneous – cosmology: early Universe

## 1. Introduction

Besides the expansion of the Universe and the ubiquitous presence of the fossil cosmological radiation, the Big Bang Nucleosynthesis (BBN) is one pillar of modern cosmology. It allows, in principle, the derivation of the baryonic density of the universe (see for reviews Schramm & Turner 1998, Sarkar 1996, 1999 and Olive et al. 2000). The determination of light element abundances has improved dramatically in the recent past and the planned observations of  $D$ ,  ${}^4\text{He}$ ,  ${}^6\text{Li}$  and  ${}^7\text{Li}$  should allow a precise determination (10% is a reachable goal) of the universal baryonic density, provided the precision of the model is made compatible with this objective. Taking advantage of the release of a new compilation of thermonuclear reaction rates, called NACRE (Nuclear Astrophysics Compilation of REaction rates) (Angulo et al. 1999), we have updated the standard BBN model developed at the Institut d'Astrophysique de Paris, including the analysis of the  $\text{Be}$  and  $\text{B}$  production in the Big Bang.

On the other hand, observations of light isotopes have flourished: i)  $D/H$  has been observed in absorbing clouds on the sightline of remote quasars, ii) refined observations of  ${}^4\text{He}$  have been performed in extragalactic very metal poor HII regions and in the Small Magellanic Cloud (Peimbert & Peimbert 2000), iii)

**Table 1.** Influential reactions and their sensitivity to nuclear uncertainties

Reaction \ $\Delta N/N$	$^4\text{He}$	D	$^3\text{He}$	$^7\text{Li}$	$^6\text{Li}$	$^9\text{Be}$	$^{10}\text{B}$	$^{11}\text{B}$
$^1\text{H}(p, e^+ \nu)^2\text{H}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^2\text{H}(p, \gamma)^3\text{He}$	n.s.	-0.19	0.19	0.26	-0.19	-0.27	-0.18	0.20
$^2\text{H}(d, \gamma)^4\text{He}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^2\text{H}(d, n)^3\text{He}$	n.s.	-0.09	0.06	0.12	-0.09	-0.09	-0.08	0.19
$^2\text{H}(d, p)^3\text{H}$	n.s.	-0.03	-0.04	0.01	-0.03	0.04	-0.03	0.03
$^2\text{H}(\alpha, \gamma)^6\text{Li}$	n.s.	n.s.	n.s.	n.s.	21.	n.s.	10.	n.s.
$^3\text{H}(d, n)^4\text{He}$	n.s.	n.s.	n.s.	-0.07	n.s.	-0.13	-0.04	-0.07
$^3\text{H}(\alpha, \gamma)^7\text{Li}$	n.s.	n.s.	n.s.	0.24	n.s.	0.24	0.06	0.24
$^3\text{He}(^3\text{He}, 2p)^4\text{He}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^3\text{He}(\alpha, \gamma)^7\text{Be}$	n.s.	n.s.	n.s.	0.39	n.s.	0.21	n.s.	0.40
$^2^4\text{He}(\alpha, \gamma)^{12}\text{C}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.01
$^2^4\text{He}(n, \gamma)^9\text{Be}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^6\text{Li}(p, \gamma)^7\text{Be}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^6\text{Li}(p, \alpha)^3\text{He}$	n.s.	n.s.	n.s.	n.s.	-0.18	n.s.	-0.18	n.s.
$^7\text{Li}(p, \gamma)^8\text{Be}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^7\text{Li}(p, \alpha)^4\text{He}$	n.s.	n.s.	n.s.	-0.25	n.s.	-0.25	-0.07	-0.24
$^7\text{Li}(\alpha, \gamma)^{11}\text{B}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.39
$^7\text{Li}(\alpha, n)^{10}\text{B}$				Q < 0				
$^7\text{Be}(p, \gamma)^8\text{B}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.01
$^7\text{Be}(\alpha, \gamma)^8\text{B}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.81
$^9\text{Be}(p, \gamma)^{10}\text{B}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	0.04	n.s.
$^9\text{Be}(p, pn)^2^4\text{He}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^9\text{Be}(p, d)^2^4\text{He}$	n.s.	n.s.	n.s.	n.s.	n.s.	-0.13	-0.02	-0.01
$^9\text{Be}(p, \alpha)^6\text{Li}$	n.s.	n.s.	n.s.	n.s.	n.s.	-0.13	-0.02	n.s.
$^9\text{Be}(\alpha, n)^{12}\text{C}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.01
$^{10}\text{B}(p, \gamma)^{11}\text{C}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.01
$^{10}\text{B}(p, \alpha)^7\text{Be}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.38	n.s.
$^{11}\text{B}(p, \gamma)^{12}\text{C}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
$^{11}\text{B}(p, n)^{11}\text{C}$				Q < 0				
$^{11}\text{B}(p, \alpha)^2^4\text{He}$	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.	-0.78
$^{14}\text{N}(p, \alpha)^{11}\text{C}$				Q < 0				

$\Delta N/N \equiv N_h/N_i - 1$

n.s.: not significant ( $|\Delta N/N| < 0.01$ )

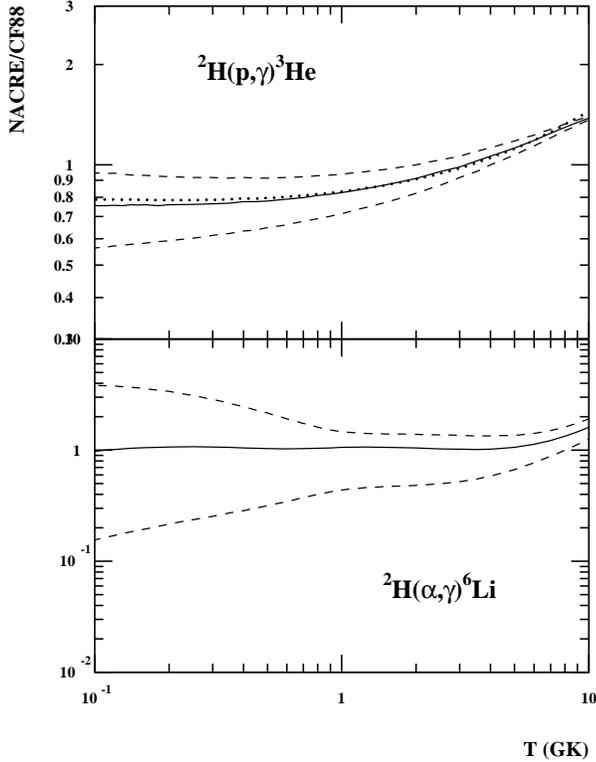
Q < 0: no tabulated reverse rates available for endoenergetic reactions.

the  $^6\text{Li}$  abundance has been determined in two halo stars, iv) high quality  $^7\text{Li}$  observations in the halo stars have been accumulated. A review of the present data can be found in Olive et al. (2000) and Tytler et al. (2000). Thus, it is timely to reassess the determination of the baryonic density of the Universe in the light of advances in nuclear physics and astronomical observations.

In Sect. 2, we present the new compilation of the reaction rates and compare it with the classical Caughlan-Fowler (1988) one; we evaluate the sensitivity of the different light element abundances to the change of each relevant reaction rate; BBN calculations are performed using i) recommended values of the reaction rates and ii) extreme values obtained from the low and high rate limits. In Sect. 3, we discuss the astrophysical status of each isotope, both observationally and theoretically in order to confront it to the BBN calculation; we deduce the baryonic density of the Universe. Finally, we draw conclusion in Sect. 4 and stress the importance of precise measurements of a few key nuclear cross sections and refined abundance determinations of D and  $^6\text{Li}$ .

## 2. Nuclear physics and Big bang nucleosynthesis

The new compilation of Angulo et al. (1999) of thermonuclear reaction rates for astrophysics, includes 86 charged-particle induced reactions corresponding to the proton capture reactions involved in the cold pp-chain, CNO cycle, NeNa and MgAl chains. The BBN network is constituted by about 60 reactions which participate to primordial nucleosynthesis up to  $^{11}\text{B}$ . 22 of these reactions are covered by the NACRE compilation. The main innovative features of NACRE with respect to the former compilation Caughlan & Fowler (1988) are the following: (1) detailed references are provided to the source of original data; (2) uncertainties are analyzed in detail, realistic lower and upper bounds of the rates are provided; (3) the rates are given in tabular form, available also electronically on the World-Wide-Web. For these reasons, we can adopt the NACRE recommended rates for the calculation of the yields and use the upper and lower limits of the rates to test the sensitivity of the abundances to the nuclear uncertainties. As the origins for these uncertainties are documented in Angulo et al. (1999), we do not discuss them



**Fig. 1.** Two particularly uncertain reaction rates:  $D(p, \gamma)^3\text{He}$  and  $D(\alpha, \gamma)^6\text{Li}$  (NACRE/Caughlan-Fowler 1988- CF88) solid line: mean ratio, dashed line: NACRE upper limit/CF88 and NACRE lower limit/CF88. The dotted line ( $D(p, \gamma)^3\text{He}$  reaction) represents the small effect of the Schmidt et al. (1996) correction not included in the NACRE compilation.

here unless they show a significant effect on yields. We calculated the isotopic abundances as a function of  $\eta_{10}$  between 1 and 10, changing one single reaction at a time. For each reaction we made a calculation with the high and low NACRE limits while the remaining reaction rates were set to their recommended NACRE value. Then we calculated, the maximum of the quantity  $\Delta N/N \equiv N_{\text{high}}/N_{\text{low}} - 1$  within the range of  $\eta_{10}$  variations for each of the 8 isotopes. Positive (resp. negative) values correspond to higher (resp. lower) isotope production when the high rate is used instead of the low one. Note however that following the  $\Delta N/N$  definition, the positive values are not bound while the negative values are bound by -1. Hence, for instance (see Table 1),  $\Delta N/N = +10$  (resp. -0.78) means that the isotope yield is 11 times higher (resp. 4.5 times lower) with the high rate than with the low one. The corresponding results are shown in Table 1.

For three of these reactions, the test has not been made because the NACRE compilation does not provide high and low limits for the reverse rate of endoenergetic reactions ( ${}^7\text{Li}(\alpha, n){}^{10}\text{B}$ ,  ${}^{11}\text{B}(p, n){}^{11}\text{C}$  and  ${}^{14}\text{B}(p, \alpha){}^{11}\text{C}$ ). The reverse recommended rate can be calculated from the usual formulas. However, the low and high rates are only tabulated and limited down to temperatures chosen in order that the reaction rate remains above the lower limit of  $N_A \langle \sigma v \rangle \leq 10^{-25} \text{ cm}^3$

$\text{mol}^{-1} \text{ s}^{-1}$ . For  $Q < 0$  reactions, the reverse rate is higher than the direct tabulated one but limited by  $N_A \langle \sigma v \rangle \leq 10^{-25} \text{ cm}^3 \text{ mol}^{-1} \text{ s}^{-1}$  times the *reverse ratio*.

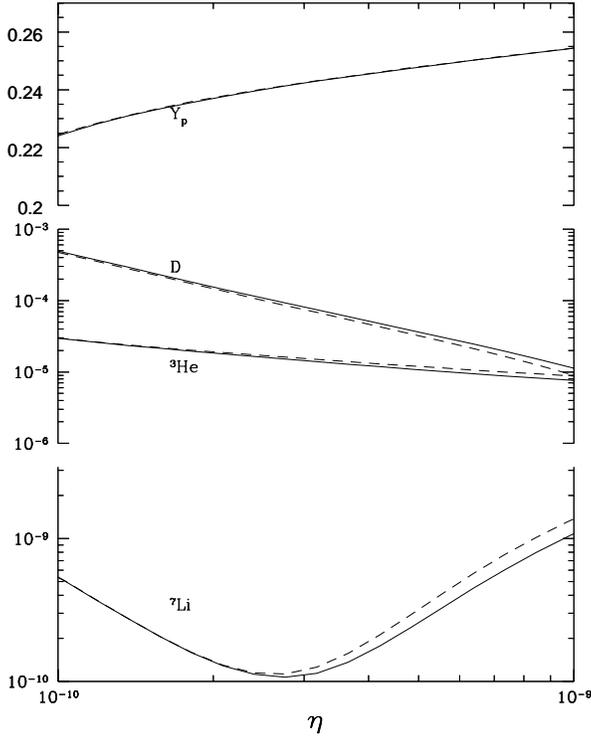
In the analysis of yield uncertainties, one should keep in mind that the guidelines for the NACRE compilation favoured conservative upper and lower limits for the rates in order that the actual rate be within these limits with a high degree of confidence. For instance, when incompatible data sets were present, and if the differences could not be resolved by analysing the publications alone the high and low limits were set in order to incorporate all data sets. In some case (e.g.  $D(\alpha, \gamma)^6\text{Li}$ ) the incompatibility is between experimental data and theoretical results making very problematic the interpretation of the rate uncertainty in term of probability distributions. When only an upper limit is available experimentally, as in previous compilations, its contribution is weighted by a 0., 0.1 and 1. factor respectively. This again makes difficult the probabilistic interpretation of rate uncertainties. Nevertheless, few NACRE reaction rates are at the origin of a significant uncertainty (Table 1).

The  $D(p, \gamma)^3\text{He}$  NACRE reaction rate is responsible for a 20–30% uncertainty on most isotopes. It comes from the dispersion of experimental results. Note that the incompatibility of the two data set at low energy reported in Angulo et al. (1999) has been removed after a correction factor (Schmidt et al. 1996) has been applied to Schmidt et al. (1995) data to account for an unsuspected experimental bias. To check the effect of this rate update, we reiterate the NACRE calculation by fitting the experimental data points up to 2 MeV but with the corrected Schmidt et al. (1995, 1996) data. Since it affects only the lowest energies, it has a negligible effect in the domain of BBN (see Fig. 1).

The most dramatic effect comes from the  $D(\alpha, \gamma)^6\text{Li}$  reaction which induces uncertainties of a factor 22 and 11 on the  ${}^6\text{Li}$  and  ${}^{10}\text{B}$  yields. This rate uncertainty originates from the discrepancy between theoretical low energy dependence of the S-factor and experimental data (Kiener et al. 1991) obtained with the coulomb break-up technique (see Kharbach & Descouvemont (1998) for a recent comparison between theories and experiment). This reaction clearly deserves further experimental effort. The reactions  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  and  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  induce a significant (25–40% each) uncertainty on  ${}^7\text{Li}$  production. For these reactions, the rate uncertainties come from the dispersion (systematic errors) of non resonant experimental data at low energy.

Uncertainties on *BeB* isotope yields remain negligible when compared with the gap between calculated values and observational limitations. At maximum, a factor of  $\approx 4$  uncertainty on  ${}^{11}\text{B}$  at low  $\eta$  arises from the influence of the  ${}^{11}\text{B}(p, \alpha){}^8\text{Be}$  reaction. However, the NACRE compilation covers only 22 of the 60 reactions involved in Big Bang Nucleosynthesis. In particular, *BeB* yield uncertainties are most likely dominated by uncertainties in reaction rates not included in the NACRE compilation.

In front of the large systematic uncertainties on the observational abundance data (Sect. 3.1), it seems premature to elabo-



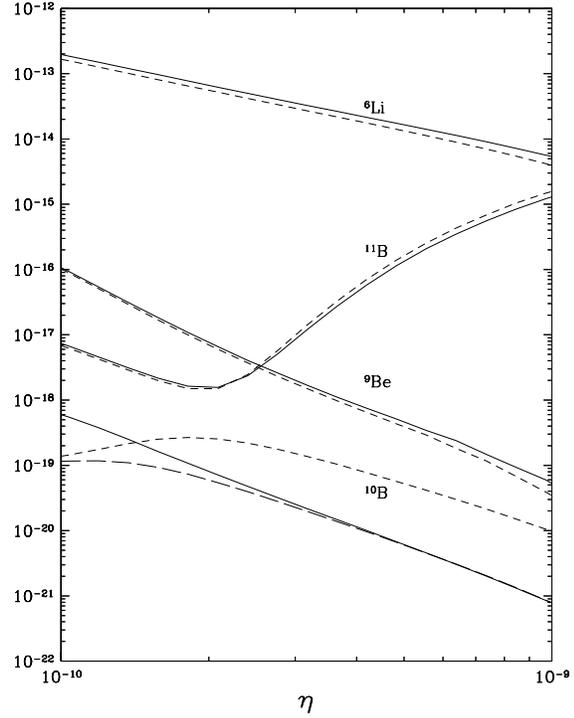
**Fig. 2.** Theoretical primordial abundances of  ${}^4\text{He}$  (by mass),  $D$ ,  ${}^3\text{He}$  and  ${}^7\text{Li}$  (by number) vs the baryon/photon ratio, using the reaction rates from NACRE (full lines) and GF88 (dashed lines).

rate complex statistical procedures to get very precise theoretical uncertainties on the primordial abundances.

Indeed, extensive studies have used Monte-Carlo techniques to estimate the theoretical uncertainties (Krauss & Romanelli 1990, Smith et al. 1993, Fiorentini et al. 1998, Olive et al. 2000, Nollet & Burles 2000). These powerful methods have proven their efficiency in various domains (e.g. simulations of high energy physics experiment) provided that the probability distribution involved is known. Concerning our approach, since the values given by the NACRE compilation do not represent statistical confidence level, but upper and lower limits, they are not directly appropriate to Monte-Carlo calculations, but they include both statistical and systematic errors (see above).

We estimate the uncertainties performing two global calculations, one with all the reaction rates set to their lower limits, and the second one with all the reaction rates set to their higher limits (dashed lines in Figs. 4 and 5). This method could lead to compensation (according to the signs of individual uncertainties displayed in Table 1) between production and destruction and therefore to underestimate the global uncertainties in some cases. The advantage of this technique is simplicity and transparency. But the disadvantage is that it does not allow to derive a confidence level, in the statistical sense.

The primordial abundances of the light elements  $D$ ,  ${}^3\text{He}$  and  ${}^7\text{Li}$  are governed by the expansion rate of the Universe and the cooling it induces. Under the classical assumptions, (homogeneity and the isotropy of the Universe and standard particle physics: three light neutrino species, neutron lifetime



**Fig. 3.** Theoretical primordial abundances of  ${}^6\text{Li}$ ,  ${}^9\text{Be}$ ,  ${}^{10}\text{B}$  and  ${}^{11}\text{B}$  (by number) vs the baryon/photon ratio,  $\eta$ , using the reaction rates from NACRE compilation (full lines) and CF88 (dashed lines). The long-dashed line associated to  ${}^{10}\text{B}$  corresponds to the Rauscher & Raimann (1997) evaluation.

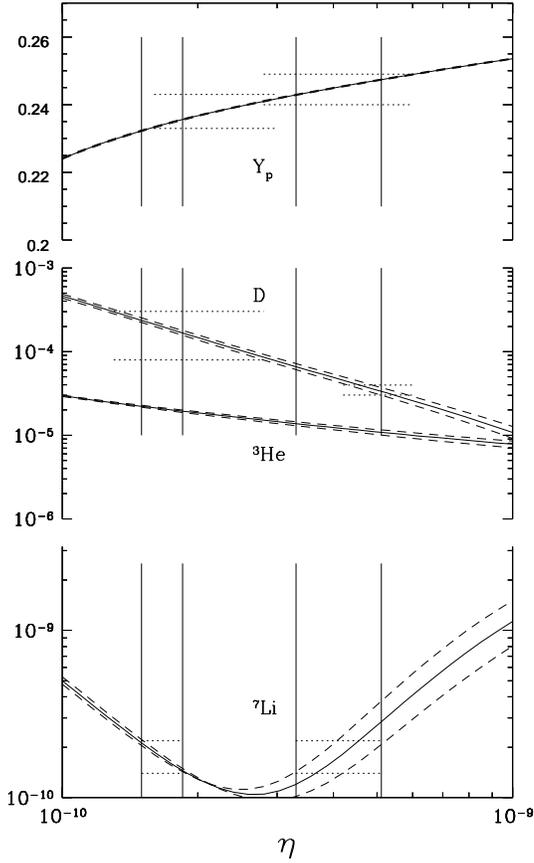
equal to 887 seconds) the abundances depend only on the baryon to photon ratio  $\eta$ , related to the baryonic parameter by  $\eta_{10} = 273\Omega_B h^2$  with  $h = H/100 \text{ km s}^{-1} \text{ Mpc}^{-1}$  (see e.g. for details Olive et al. 2000).

We do not include the small corrections on the  ${}^4\text{He}$  mass fraction due to Coulomb, radiative and finite temperature effects, finite nucleon mass effects and differential neutrino heating (Sarkar 1999, Lopez & Turner 1999) since these corrections lead to effects much less than the uncertainties on the observational data.

The network extends up to  ${}^{11}\text{C}$  (decaying into  ${}^{11}\text{B}$ ), the leakage is taken into account through the reaction  ${}^{11}\text{C}(n, 2\alpha){}^4\text{He}$ .

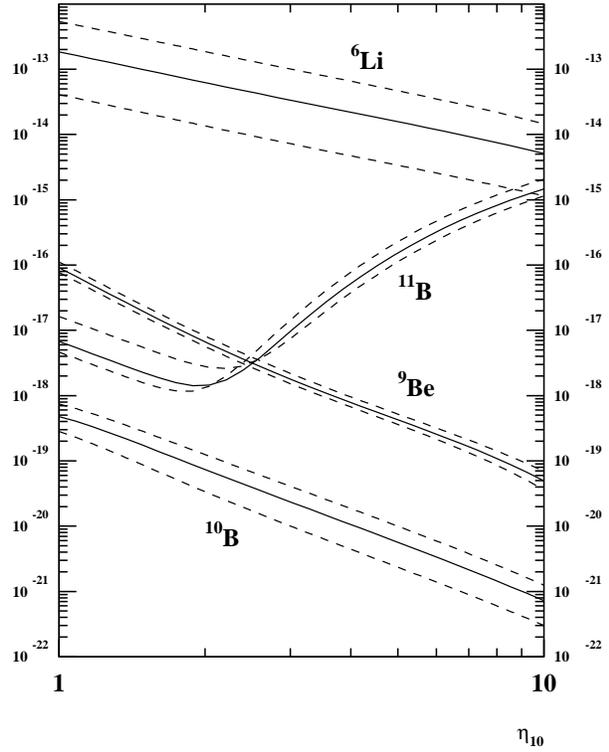
In Figs. 2 and 3, we compare the results obtained with i) the NACRE recommended reaction rates (solid lines) and ii) the CF88 ones (dashed lines). There is no significant difference except for  ${}^7\text{Li}$  at high  $\eta$ . In this range,  ${}^7\text{Li}$  comes from  $D(p, \gamma){}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  followed by electron capture. So changes in the first rate result directly in changes of the final  ${}^7\text{Li}$  yield.  ${}^{10}\text{B}$  presents the largest difference due to the revise  ${}^{10}\text{B}(p, \alpha){}^7\text{Be}$  destruction reaction rate. The NACRE rate is several orders of magnitude higher due to the inclusion (Rauscher & Raimann 1997) of a 10 keV,  $5/2^+$  resonance. However, there is no astrophysical and cosmological consequences since  ${}^{10}\text{B}$  is essentially of spallative origin (Vangioni-Flam et al. 2000).

Figs. 4 and 5 present the updated theoretical primordial abundances from  $D$  to  ${}^{11}\text{B}$  using the NACRE compilation



**Fig. 4.** Theoretical primordial abundances of  ${}^4\text{He}$  (by mass),  $D$ ,  ${}^3\text{He}$  and  ${}^7\text{Li}$  (by number) vs the baryon/photon ratio,  $\eta$ , using the reaction rates from the NACRE compilation. Full lines: mean values of the reaction rates. Dashed lines: extreme value of the reaction rates (for details see Sect. 2). Horizontal dotted lines indicate the error boxes related to different observations,  ${}^4\text{He}$  left: Fields & Olive (1998),  ${}^4\text{He}$  right: Izotov & Thuan (1998).  $D$  left: Webb et al. (1997),  $D$  right: Tytler et al. (2000).  ${}^7\text{Li}$ : Molaro (1999) and Ryan et al. (1999a). Vertical full lines are deduced from the error box of  ${}^7\text{Li}$ .

(mean values and extreme ones).  $D$  and  ${}^3,4\text{He}$  are almost not affected. Due to the uncertainty of the  $D(p, \gamma){}^3\text{He}$ , the  ${}^7\text{Li}$  abundance at  $\eta > 3$  is affected by a significant error (about 30% to be compared to the 42% one mentioned by Olive et al. 2000 deduced from the Smith et al. 1993 analysis). At  $\eta < 3$ , the  ${}^7\text{Li}$  uncertainty is reduced due to improvements in the derivation of the S factor of the  $T(\alpha, \gamma){}^7\text{Li}$  reaction (Angulo et al. 1999). This is the result of the high precision data provided by Brune et al. (1994) and spanning the entire energy range of interest to BBN nucleosynthesis. Considering only the precise Brune et al. (1994) data would even reduce the rate uncertainty. However, in this specific case, with our method, error compensation occurs between the  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  and  $T(\alpha, \gamma){}^7\text{Li}$  reaction rates as shown in Table 1. From the same table, one sees that the maximized uncertainties are  $\pm 25\%$ . Consequently on Fig. 4, the uncertainty is somewhat underestimated, which does not affect significantly the general conclusions. On the contrary, for  $\eta > 3$  region, the errors on the reaction rates  $D(p, \gamma){}^3\text{He}$ ,



**Fig. 5.** Theoretical primordial abundances of  ${}^6\text{Li}$ ,  ${}^9\text{Be}$ ,  ${}^{10}\text{B}$  and  ${}^{11}\text{B}$  (by number) vs the baryon/photon ratio,  $\eta$ , using the reaction rates from NACRE. Full lines: mean values of the reaction rates. Dashed lines: extreme limits of the reaction rates.

${}^3\text{He}(\alpha, \gamma){}^7\text{Li}$  add up and therefore the uncertainties are not underestimated.

${}^6\text{Li}$  has a particularly large error bar due to the poor knowledge of  $D(\alpha, \gamma){}^6\text{Li}$ . The maximum value of the primordial  ${}^6\text{Li}/H$  (at low  $\eta$ ) which is of the order of  $5 \times 10^{-13}$  may not be out of reach of future measurements in halo stars; it represents a factor 10 below the  $6/7$  value measured at present in old stars ( $[\text{Fe}/H] = -2.3$ ). The results presented here are in fair agreement with previous calculations (Thomas et al. 1993, Schramm 1993, Delbourgo-Salvador & Vangioni-Flam 1993, Vangioni-Flam et al. 1999). We confirm that primordial abundances of  $\text{Be}$  and  $\text{B}$  are negligible even in the most favorable case, and spallation remains the main mechanism to produce them in the course of the galactic evolution.

### 3. Astrophysical and cosmological discussion

#### 3.1. Astrophysical aspects

In the following, we decline the astrophysical observational and theoretical status of each isotope of interest and their possible evolution since the Big Bang in order to define reasonable error boxes to prepare the confrontation to the theoretical calculations.

### 3.1.1. Deuterium

$D$  is particularly sensitive to the baryon/photon ratio,  $\eta$ , and has been considered up to now as the best baryometer (e.g. Reeves 1994). However, due to a certain confusion on  $D/H$  abundance evaluations, both at high redshifts and in the local Galaxy, some care has to be taken in the cosmological use of Deuterium. Let us present a brief overview of the observations.

$D$  is measured in three astrophysical and/or cosmological sites i) the local interstellar medium, ISM ( $D_{ISM}$ ), ii) the protosolar nebula ( $D_{ps}$ ), iii) the cosmological clouds ( $D_{cc}$ ). These three values serve as signposts to follow the evolution of  $D$  in the Universe and in the Galaxy. Deuterium, due to its fragility is completely burnt in stars. Thus, if no production mechanism is at work, we must have  $D_{cc} > D_{ps} > D_{ISM}$ .

The local  $D$  abundance, inferred from UV observations of the nearby ISM, estimated to  $(1.6 \pm 0.1) \times 10^{-5}$  (Linsky et al. 1995), is probably not unique, ranging from  $5. \times 10^{-6}$  to about  $2. \times 10^{-5}$  (Vidal-Madjar et al. 1998, Lemoine et al. 1999, Vidal-Madjar 2000). These variations are lacking explanations. Thus, there is an ambiguity on the true local  $D/H$  value which, by the way, serves as a normalisation for the chemical evolutionary models. These discrepancies weaken the predictive ability of the evolutionary models to derive the primordial  $D$  abundance.

$D/H$  ratios are measured in the solar system (Jupiter, Saturn, Uranus, Neptun, comets). This allows one to derive a precise protosolar value of  $(3 \pm 0.3) \times 10^{-5}$  (Drouart et al. 1999), somewhat higher than the estimate of Geiss & Gloeckler (1998)  $(2.1 \pm 0.5) \times 10^{-5}$ .

$D/H$  has also been determined in absorbing clouds on the sightlines of quasars. On the one side, Tytler et al. (2000) (and reference therein) have found three absorption systems in which  $D/H$  are i)  $(3.24 \pm 0.3) \times 10^{-5}$ , ii)  $4_{-0.6}^{+0.8} \times 10^{-5}$ , iii)  $< 6.7 \times 10^{-5}$ . As a fair representation of these data, we adopt the following range: 3. to  $4. \times 10^{-5}$ . This estimate, if identified with the primordial one, is uncomfortably close to the protosolar one, since it implies a very small  $D$  destruction all along the galactic evolution corresponding to a small variation of the star formation rate from the birth of the galaxy up to now, in contradiction with the general trend indicated by the strong increase of the cosmic star formation rate vs redshift ( $0 < z < 2$ ) (Blain et al. 2000, Madau 2000). On the other side, high values of  $D/H$  have been reported concerning the quasar QSO 1718+4807 ( $z = 0.701$ ) namely,  $D/H = (2.5 \pm 0.5) \times 10^{-4}$  according to Webb et al. (1997) and  $8. \times 10^{-5} < D/H < 5.7 \times 10^{-4}$  according to Tytler et al. (2000). Note that the analysis of Levshakov et al. (1999) allowing non gaussian velocity distributions leads to lower values. Consequently, we adopt a second data box bounded by  $8. \times 10^{-5} < D/H < 3. \times 10^{-4}$ .

### 3.1.2. Helium-3

This isotope is produced in comparable amount to that of deuterium, but contrary to the latter, its stellar and galactic story is not simple. Its production and destruction are model dependent (Vassiliadis & Woods 1993, Charbonnel 2000). In spite of great

effort directed to its abundance determination in HII regions and planetary nebula (Balsler et al. 1999, Bania & Rood 2000)  ${}^3He$  cannot be used, at the moment, as a reliable cosmic baryometer (Olive et al. 1995, Galli et al. 1997) since it is very difficult to extrapolate its abundance back to its primordial value.

### 3.1.3. Helium-4

The primordial abundance of  ${}^4He$  by mass,  $Y_p$ , is measured in low metallicity extragalactic HII regions (for a review see Kunth & Ostlin 2000). In addition to the primordial component,  ${}^4He$  is also produced in stars together with oxygen and nitrogen through global stellar nucleosynthesis. Therefore, in order to extract the primordial component from the observational data, it is necessary to extrapolate back the observed  ${}^4He$  value down to zero metallicity. Olive et al. (1997) selected 62 blue compact galaxies and obtained  $Y_p \sim 0.234$ . Izotov & Thuan (1998) pointed out that the effect of the HeI stellar absorption has more importance than previously thought and they reported  $Y_p = 0.245 \pm 0.004$ . Recently, Fields & Olive (1998) reanalyzed the observational data and reported  $Y_p = 0.238 \pm (0.002)_{stat} \pm (0.005)_{syst}$  where the errors are  $1 \sigma$  values. The new determination  $Y_p = 0.2345 \pm 0.0030$  by Peimbert & Peimbert (2000) on the basis of observations of HII regions in the Small Magellanic Cloud points towards the lowest helium value proposed by Fields & Olive (1998). In this context, two data boxes emerge: i)  $Y_p = 0.245 \pm 0.004$  and ii)  $Y_p = 0.238 \pm 0.005$ .

### 3.1.4. Lithium-6,7

Recent advances on the determination of  $Li$  in halo stars (Spite et al. 1996, Bonifacio & Molaro 1997, Molaro 1999, Smith et al. 1998, Ryan et al. 1999a) indicate that the Spite plateau is exceptionally thin ( $< 0.05$  dex). This small dispersion, together with the presence of  ${}^6Li$  in two halo stars (Smith et al. 1993, 1998, Hobbs & Thorburn 1994, 1997, Cayrel et al. 1999) indicates that the stellar destruction of  ${}^7Li$  if any, is very limited (less than  $\sim 0.1$  dex, see Ryan et al. 1999a).  ${}^6Li$  is however of cosmological interest since, being more fragile than  ${}^7Li$ , its mere presence in the atmosphere of halo stars confirms that  ${}^7Li$  is essentially intact in these stars (Vangioni-Flam et al. 1999, Fields & Olive 1999). This, combined with the very small dispersion around the average of the Spite plateau adds confidence in interpreting it as indicative of the primordial  $Li$  abundance (especially at the lowest metallicities, where the contamination by spallation is expected to be negligible (Ryan et al. 1999b). Stellar modelisation should adapt to this constraint. Indeed, simple models of lithium evolution predict little or no depletion (Deliyannis et al. 1990), thus comforting the primordial nature of lithium in metal poor halo stars. However, three different mechanisms of alteration of lithium in halo stars have been suggested i) diffusion/gravitational settling (Michaud 2000 and references therein), ii) rotational mixing (Chaboyer 1998, Pinsonneault et al. 1999) and iii) stellar winds (Vauclair & Charbonnel 1995). Some combinations of these three mechanisms have to be envisioned. There is a paradox between the absence of dispersion and

the number of the processes which could produce a potential dispersion. This implies either a curious statistical compensation or, more radically, that these physical mechanisms are intrinsically irrelevant. However, metallicity independent depletion mechanisms (for instance mixing induced by gravity waves) cannot be totally excluded (Cayrel, private communication).

Consequently, we take the observed value of the Spite plateau including the observational dispersion ( $A(Li) = 2.2 \pm 0.04$ ) to which we add 0.1 dex to account the maximum  $Li$  stellar depletion. For the primordial lithium this corresponds to the following range  $1.4 \times 10^{-10} < {}^7Li/H < 2.2 \times 10^{-10}$ . This evaluation is in fair agreement with that of Olive et al. (2000) but it is narrower than that of Tytler et al. (2000) who have enlarged the limit of depletion to allow agreement with their low  $D/H$  measurement.

In the following, due to the high observational quality and the large sample analyzed (more than 70 objects),  ${}^7Li$  is used as a baryometer, keeping in mind that this isotope has the peculiarity to allow to possible solutions depending on the side of the lithium valley.

### 3.1.5. Beryllium and Boron

Abundance observations of elemental  $Be$  and  $B$  in very metal poor stars in the halo have made great progresses in the recent years (Gilmore et al. 1992, Duncan et al. 1992, Boesgaard & King 1993, Ryan et al. 1994, Duncan et al. 1997, Garcia-Lopez et al. 1998, Primas et al. 1999, Primas 2000). These observations concern indeed galactic evolution; the lowest observed values (of the order of  $10^{-13}$ ) are much higher than the BBN calculated abundances. We confirm that BBN calculated abundances of  ${}^9Be$ ,  ${}^{10}B$  and  ${}^{11}B$  are negligible with respect to the measured ones in the more metal poor stars. The origin of these elements can be explained in term of spallation of fast carbon and oxygen in the early Galaxy (Vangioni-Flam et al. 2000).

### 3.2. Baryonic density of the universe

Once the different error boxes corresponding to the observed isotope abundances corrected for evolutionary effects are established, we can compare them to the predictions of the BBN calculations. As different  $D$  and  ${}^4He$  measurements are dichotomic, contrary to  ${}^7Li$ , we put emphasis on this last isotope to determine a possible range of baryonic densities. As shown in Fig. 4, considering  ${}^7Li$  alone, two possible ranges emerge: i)  $1.5 < \eta_{10} < 1.9$ , ii)  $3.3 < \eta_{10} < 5.1$ . For  $h = 0.65$ , we get i)  $0.013 < \Omega_B < 0.019$  and ii)  $0.029 < \Omega_B < 0.045$ .

The first range is in good concordance with the error boxes related to high  $D$  and low  ${}^4He$ . However, the largest measured value of  $D/H$  seems excluded ( $D/H < 3. \times 10^{-4}$ ). The second one, on the right side of the diagram, is in fair agreement with a lower  $D/H$  (except the lowest measured value,  $D/H = 3. \times 10^{-5}$ ) and a higher  ${}^4He$  (except also the highest value 0.25). At this stage of the analysis, we have to admit that two ranges of baryonic density have to be taken into account, only future observations will help to remove the ambiguity.

It is worth comparing the baryonic density to that of the luminous matter ( $\Omega_L$ ) in the Universe to infer the amount of the baryonic dark matter. Recent estimates of  $\Omega_L$  range between 0.002 and 0.004 (Salucci & Persic 1999), which is lower than both  $\Omega_B$  obtained. The difference makes necessary baryonic dark matter. Focusing on spiral galaxies the amount of luminous matter is estimated to  $\Omega_{LS} = 1.44_{-0.2}^{+1.55} \times 10^{-3}$  (Salucci & Persic 1999). Considering that the dynamical mass of the halo of spiral galaxies is about ten times higher than that of the disk, the corresponding  $\Omega_{HS}$  is about 0.015. In both cases ( $\Omega_B \approx 0.015$  or  $\Omega_B \approx 0.04$ ) all the dark matter in the halo of our Galaxy could in principle be baryonic. Note that since eight years of searches for microlensing events by the MACHO and EROS collaborations toward the Magellanic clouds have revealed only a few events. The fraction of the halo in the form of dark massive compact objects, using a typical model, is estimated to only 20% by Alcock et al. (2000) in agreement with the limits given by Lasserre et al. (2000). On the other hand, the observations of the Lyman alpha forest clouds between the redshifts 0 and 5, lead to a corresponding  $\Omega_B$  of about 0.03 ( $\pm 0.01$ ), taking into account the uncertainty related to ionised hydrogen (Riediger et al. 1998). This value is thought to reflect the bulk of the baryons at large scale. It is more consistent with our high  $\Omega_B$  range.

## 4. Conclusion

Big bang nucleosynthesis has been studied since a long time, but it deserves permanent care since it gives access to the baryon density which is a key cosmological parameter. This work has been aimed at integrating the last development in both fields of nuclear physics and observational abundance determination of light elements.

1. The update of the reaction rates of the BBN using the NACRE compilation does not lead to crucial modifications of the general conclusions concerning the baryonic content of the Universe. The average values of the abundances of isotopes of cosmological interest are in general similar to that calculated on the basis of the Caughlan-Fowler (1988) compilation.
2. However, the modification of the  $D(p, \gamma){}^3He$  reaction rate leads to a  ${}^7Li$  abundance slightly lower at  $\eta > 3$ . But the uncertainty on this reaction rate remains high ( $\pm 30\%$ ). At  $\eta < 3$ , the revision of the  $T(\alpha, \gamma){}^7Li$  reaction rate leads to a reduction of the uncertainty of the calculated  ${}^7Li$  abundance. However this reaction, together with the  ${}^7Li(p, \alpha){}^4He$ , remains the main source of the  ${}^7Li$  uncertainty at low  $\eta$ .
3. The abundance of  ${}^{10}B$  is modified by the new  ${}^{10}B(p, \alpha){}^7Li$  reaction rate, but there are no cosmological consequences.
4.  ${}^6Li$  is affected by the large uncertainty of the  $D(\alpha, \gamma){}^6Li$  reaction. However,  ${}^6Li$  is essentially of spallative origin.
5. Owing to the high observational reliability of the  ${}^7Li$  abundance data with respect to the  $D$  data available both rare and debated, we choose it as the leading baryometer, since it appears that the primitive  ${}^7Li$  is almost intact in halo stars. Due to the competition between  $T(\alpha, \gamma){}^7Li$  and  $D(p, \gamma){}^3He(\alpha, \gamma){}^7Be$  (e  $\nu$ )  ${}^7Li$ , the curve of  ${}^7Li$  vs  $\eta$

presents a valley shape. Consequently, the observational error box of  ${}^7\text{Li}$  leads to two ranges of  $\eta$ :  $1.5 < \eta < 1.9$  and  $3.3 < \eta < 5.1$  (corresponding to  $0.013 < \Omega_B < 0.019$  and  $0.029 < \Omega_B < 0.045$  for  $h=0.65$ ). In both cases, all the dark matter in the halo of our Galaxy could be baryonic. However, only a fraction of 20% is detected through microlensing events in the direction of the Magellanic clouds.

6. These two  $\eta$  ranges are confronted to the other available cosmologically relevant isotopes, namely  $D$  and  ${}^4\text{He}$ . The first  $\eta$  range agrees with a high  $D$  and low  ${}^4\text{He}$  values, the second range is in concordance with a low  $D$  and high  ${}^4\text{He}$  values. At present, none of these solutions can be excluded.

7. In the future, on the nuclear physics front, it would be important to (re-)measure the  $D(\alpha, \gamma){}^6\text{Li}$  reaction to reduce the uncertainty on the calculated  ${}^6\text{Li}$  abundance. High precision measurements over the full energy range of interest to BBN of the  $D(p, \gamma){}^3\text{He}$ ,  ${}^3\text{He}(\alpha, \gamma){}^7\text{Be}$  and  ${}^7\text{Li}(p, \alpha){}^4\text{He}$  reactions would also reduce the uncertainty on  ${}^7\text{Li}$  abundance calculations. On the astronomical front, more data on  $D$  in absorbing clouds on the sightlines of quasars at different redshifts are mandatory to remove the ambiguity. However, if the large scale  $D$  dichotomy remains, it will be time to invoke specific mechanisms of  $D$  production and destruction like photodisintegration of  $D$  and  ${}^4\text{He}$  by  $\gamma$  ray quasars (blazars) (Cassé & Vangioni-Flam 1997) and/or nuclear spallation. The observations of  ${}^6\text{Li}$  in two halo stars has been a great progress and a determination of its abundance in very metal poor stars should be pursued. It will help to constrain even more stringently the possible lithium depletion in these stars and comfort definitively the primordial status of the Spite plateau. Together with nuclear improvements, refined  ${}^6\text{Li}$  measurements in very metal poor stars (possibly via the VLT) could perhaps lead us towards the primordial  ${}^6\text{Li}$  abundance.

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**Note added in proof:** A more detailed analysis of uncertainties, including uncompensated errors on the reaction rates will be given in a subsequent paper.

## References

- Alcock C.(MACHO), 2000, preprint, astro-ph/0001272
- Angulo C., Arnould M., Rayet M., et al., (The NACRE collaboration), 1999, Nucl. Phys. A656, 3 and <http://pntpm.ulb.ac.be/nacre.htm>
- Balsler D.S., Bania T.M., Rood R.T., Wilson T.L., 1999, ApJ 510, 759
- Bania T., Rood R., 2000, In: da Silva L., de Meideros R., Spite M. (eds.) The light Elements and their Evolution. IAU Symp. 198, ASP Conf. Series, in press
- Blain B., Jameson A., Smail I., et al., 2000, astro-ph/9906311
- Boesgaard A.M., King J.R., 1993, AJ 106, 2309
- Bonifacio P., Molaro P., 1997, MNRAS 285, 847
- Brune C.R., Kavanagh R.W., Rolfs C., 1994, Phys. Rev. C50, 2205
- Cassé M., Vangioni-Flam E., 1997, In: Petitjean P., Charlot S. (eds.) Structure and evolution of the Intergalactic medium from QSO absorption line systems. Edts Frontières, p. 331
- Cayrel R., Spite M., Spite F., et al., 1999, A&A 343, 923
- Caughlan G.R., Fowler W.A., 1988 At. Data Nucl. Data Tables 40, 283
- Chaboyer B., 1998, UAI 185, p. 25
- Charbonnel C. 2000, In: da Silva L., de Meideros R., Spite M. (eds.) The light Elements and their Evolution. IAU Symp. 198, ASP Conf. Series, in press
- Deliyannis C.P., Demarque P., Kawaler S.D., 1990, ApJS 73, 21
- Delbourgo-Salvador P., Vangioni-Flam E., 1993, In: Prantzos N., Vangioni-Flam E., Cassé M. (eds.) Origin and evolution of the elements. Cambridge University Press, p. 132
- Drouart A., Dubrulle B., Gautier D., Robert F., 1999, Icarus 140, 129
- Duncan D., Lambert D.L., Lemke M., 1992, ApJ 401, 584
- Duncan D., Primas F., Rebull L.M., et al., 1997, ApJ 488, 338
- Fields B., Olive K.A., 1998, ApJ 506, 177
- Fields B., Olive K.A., 1999, New Astron. 4, 255
- Fiorentini G., Lisi E., Sarkar S., Villante F.L., 1998, Phys. Rev. D58, 063506
- Galli D., Stanghellini L., Tosi M., Palla F., 1997, ApJ 477, 218
- Garcia-Lopez R.J., Lambert D.L., Edvardsson B., et al., 1998, ApJ 500, 241
- Geiss J., Gloeckler G., 1998, Space Sci. Rev. 84, 239
- Gilmore J., Gustafsson B., Edvardsson B., et al., 1992, Nat 357, 379
- Hobbs L.M., Thorburn J.A., 1994, ApJ 428, 25
- Hobbs L.M., Thorburn J.A., 1997, ApJ 491, 772
- Izotov Y.I., Thuan T.X., 1998, ApJ 500, 1888
- Kharbach A., Descouvemont P., 1998, Phys. Rev. C58, 1066
- Kiener J., Gils H.J., Rebel H., et al., 1991, Phys. Rev. C44, 2195
- Kunth D., Ostlin G., 2000, to appear in A&AR
- Krauss L.M., Romanelli P., 1990, ApJ 358, 47
- Lasserre T., et al. (EROS), 2000, preprint astro-ph/0002253
- Lemoine M., Audouze J., Beu Jaffel L., et al., 1999, New Astronomy 4, 23
- Levshakov S.A., Kegel W.H., Takahara F., 1999, MNRAS 302, 707
- Linsky J., Diplas A., Wood B., et al., 1995, ApJ 451, 335
- Lopez R.E., Turner M.S., 1999, Phys. Rev. D 59, 103502
- Madau P., 2000, In: VLT opening Symp., in press astro-ph/9907268
- Michaud G., 2000, In: da Silva L., de Meideros R., Spite M. (eds.) The light Elements and their Evolution. IAU Symp. 198, ASP Conf. Series, in press
- Molaro P., 1999, In: Ramaty R., Vangioni-Flam E., Cassé M., Olive K. (eds.) LiBeB, Cosmic Rays, and Related X and Gamma-Rays. ASP Conf. Series vol. 171, p. 6
- Nollet K.M., Burles S., 2000, astro-ph/0001440
- Olive K., Rood R.T., Schramm D.N., Truran J., Vangioni-Flam E., 1995, ApJ 444, 680
- Olive K.A., Steigman G., Walker T.P., 2000, in press in Phys. Rep. Astro-ph/9905320
- Olive K.A., Skillman E.D., Steigman G., 1997, ApJ 489, 1006
- Peimbert M., Peimbert A., 2000, In: da Silva L., de Meideros R., Spite M. (eds.) The light Elements and their Evolution. IAU Symp. 198, ASP Conf. Series, in press
- Pinsonneault M.H., Walker T.P., Steigman G., Narayanan V.K., 1999, ApJ 527, 180
- Primas F., Duncan D., Peterson R.C., et al., 1999, A&A 313, 545
- Primas F. 2000, In: da Silva L., de Meideros R., Spite M. (eds.) The light Elements and their Evolution. IAU Symp. 198, ASP Conf. Series, in press
- Rauscher T., Raimann G., 1997, nucl-th/9602029
- Reeves H., 1994, Rev. Mod. Phys. 66., 193
- Riediger R., Petitjean P., Mucket J.P., 1998, A&A 329, 30
- Ryan S.G., Norris I., Bessel M., Deliyannis C., 1994, ApJ 388, 184

- Ryan S.G., Norris J.E., Beers T.C., 1999a, astro-ph/9903059
- Ryan S.G., Beers T.C., Olive K.A., Fields R.D., Norris J.E., 1999b, astro-ph/9905211
- Salucci P., Persic M., 1999, MNRAS 309, 923
- Sarkar S., 1996, Rep. Prog. Phys. 59, 1493,
- Sarkar S., 1999, astro-ph/9903183
- Schramm D.N., Turner M.S., 1998, Rev. Mod. Phys. 70, 303
- Schramm D., 1993, In: Prantzos N., Vangioni-Flam E., Cassé M. (eds.) Origin and evolution of the elements. Cambridge University Press, p. 112
- Schmidt G.J., Chasteler R.M., Laymon C.M., et al., 1995, Phys. Rev. C52, R1732
- Schmidt G.J., Chasteler R.M., Laymon C.M., et al., 1996, Nucl. Phys. A607, 139
- Smith M., Kawano L., Lawrence H., Malaney R.A., 1993a, ApJS 85, 219
- Smith V.V., Lambert D.L., Nissen P.E., 1993b, ApJ 408, 262
- Smith V.V., Lambert D.L., Nissen P.E., 1998, ApJ 506, 405
- Spite M., Francois P., Nissen P.E., Spite F., 1996, A&A 307, 172
- Thomas D., Schramm D.N., Olive K.A., Fields B.D., 1993, ApJ 406, 563
- Tytler D., O'Heara J., Suzuki N., et al., 2000, astro-ph/0001318
- Vangioni-Flam E., Cassé M., Cayrel R., et al., 1999, New Ast. 4, 245
- Vangioni-Flam E., Cassé M., Audouze J., 2000, Phys. Rep. In press
- Vassiliadis E., Wood P.R., 1993, ApJ 413, 641
- Vauclair S., Charbonnel C., 1995, A&A 295, 715
- Vidal-Madjar A., Lemoine M., Ferlet R., et al., 1998, A&A 338, 694
- Vidal-Madjar A., 2000, In: da Silva L., de Meideros R., Spite M. (eds.) The light Elements and their Evolution. IAU Symp. 198, ASP Conf. Series, in press
- Webb J.K., et al., 1997, Nat 383, 250