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ASTRONOMY AND ASTROPHYSICS

Abundance of Lithium in Unevolved Halo Stars and Old Disk Stars: Interpretation and Consequences*

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Summary. High resolution spectra with high signal-to-noise ratios (typically 100) have been obtained for a few halo dwarfs with the 3ᵐ6 CFH telescope. These solar type stars are very old and extremely metal poor. The Li resonance line (λ 6707) is observed, and is essentially produced by the ^{7}Li isotope.

Although the mean metal abundance M/H varies from a factor 12 to 250 relative to the Sun, the abundance of lithium is very constant in all these stars, but the coolest ones where the convection zone is deep enough to induce ^{7}Li destruction by proton fusion.

The non-destruction of ^{7}Li in very old halo stars (of about the solar type) is to be attributed to the reduction of the size of the convective zone, reduction caused by the very small abundance of the heavy elements.

If the problem seems clear for the halo stars it is on the contrary very confusing in Population I stars. It seems however that in the old disk stars the destruction of lithium is also inhibited, probably also by a reduction of the depth of the convective zone due to the slight metal deficiency. It is pointed out, on the other hand, that among G type stars of Population I more than a half have a lithium abundance similar to that of the Hyades, although probably not half of them are as young as the Hyades.

It is suggested that the destruction of lithium in solar type stars is sometimes accelerated by the action of another process such as overshooting or turbulent diffusion, which is not always present.

We admit that the shape of the distribution of Li abundance in the Pleiades after Duncan (1981) rules out a significant destruction of lithium in the protostellar phase for solar type stars. Depletion of Lithium in halo stars by other processes is discussed and found unlikely. After discussion it is suggested that the abundance of lithium in halo dwarfs is therefore representative of the abundance of the interstellar matter which formed the stars and also that this matter itself retains the lithium abundances of the Big Bang, hardly altered.

We deduce a primordial value of the lithium abundance $11.2\,10^{-11}\,N_H$ (or, by mass $X_{Li}=5.96\,10^{-10}$).

The baryonic density of the Universe deduced from this value is compared to the densities deduced from the primordial abundance of deuterium and helium. All these densities are small, and this show that the Universe cannot be closed by nucleons.

Key words: cosmology – stellar abundances – galactic halo – galactic evolution

I. Introduction

The importance of the abundance of lithium has been stressed since many years (e.g. Herbig, 1965; Reeves, 1974; Boesgaard, 1976). At variance with the elements heavier than $A=11$, lithium is not built in the normal supernovae. It appeared soon that most of the existing lithium was probably produced in the Big Bang.

However many difficulties arise when attempts are made to compare the observed abundance of lithium with the theoretical prediction of the standard model (Wagoner, 1973) of the (hot) Big Bang: the lithium has a fragile nucleus which is destroyed by proton fusion when the temperature reaches $2\,10^6$ K. Therefore lithium can be destroyed in the central part of a protostar in formation. In a main sequence star it is destroyed as soon as the convective zone reaches the layers where temperature is larger than $2\,10^6$ K. In giant stars, it is diluted. In all the stars, its abundance can be altered by stellar winds. Differential gravitational sorting has sometimes been considered.

Finally it could be produced in some phases of the evolution of moderate mass stars (weak G-band stars, CH stars, red giants, novae etc. ...) and it is produced in interstellar matter by the cosmic rays (spallation process: Reeves et al., 1970; Meneguzzi et al., 1971).

In spite of these accumulated difficulties and of the corresponding uncertainties, the abundance of lithium has been used several times in order to try to constrain the Big Bang model (Boesgaard, 1976; Austin and King, 1977).

Owing to the far reaching consequences of the determination of the lithium abundance, we decided to try to observe this abundance in Population II dwarfs. The observations were aimed at a determination of the lithium abundance at a time when the amount of lithium produced by the cosmic rays and by stars was minimum or inexistent. Moreover the relation between stellar mass and lithium abundance in Population II was unknown: it could be expected that the comparison with the similar relation in Population I could shed some light on the confused problem of lithium destruction in proto-stars and (or) in main sequence stars. Thus 10 old Population I stars were observed in the same conditions than 13 well-known halo dwarfs. The results are compared to those obtained by Duncan (1981) and Cayrel et al. (1982) for young Population I stars. We hope that this work will contribute to a better knowledge of the process of Li destruction and of the structure of Population II stars.

II. Observations and Reductions

When it was recognized that it was possible to observe the Lithium resonance line in rather faint dwarfs at the coudé focus of

* Based on observations made with the Canada-France-Hawaii telescope

Table 1. Observing log and basic data for halo stars

	date	exp. (mn)	S/N ratio	V	V_R	m-M	u	v	w	e
HD 19445	12 8 81	75	40	8.1	+140	3.0	+156	-122	-67	0.59
	14 8 81	120	50							
	15 8 81	150	100							
HD 76932	16 2 81	40	75	5.8	+122	2.3	+49	-89	+81	0.35
HD 84937	1 6 82	120	50	8.2	-19	3.6	+153	-153	-9	0.69
HD 94028	5 6 82	90	35	8.2	+162	4.9	+42	-235	-28	0.89
HD 103095	16 2 81	60	100	6.4	-98	-0.3	-267	-150	-17	0.82
HD 134169	12 8 81	150	70	7.7	+25	2.2	+17	-1	+19	0.08
HD 140283	9 8 81	75	90	7.2	-171	2.0	+19	-107	-38	0.62
	16 8 81	60	80							
BD 20°3603	5 6 82	330	35	9.7	-243	5.2	+3	-330	-37	0.75
HD 188510	31 5 82	240	60	8.8	-201	3.2	+159	-119	+64	0.59
HD 194598	1 11 81	60	150	8.4	-247	3.4	+83	-265	-16	0.98
HD 201891	12 8 81	90	200	7.4	-45	2.5	-69	-107	-52	0.45
HD 211998	23 8 81	60	60	5.3	+25	1.5	+98	-92	-48	0.42
	24 8 81	60	60							
HD 219617	9 8 81	140	100	8.1	+10	4.0	-300	-258	-44	0.99

Table 2. Observing log and basic data for old disk stars

	date	exp (mn)	S/N ratio	V	V_R	m-M	u	v	w	e
HD 6582	12 8 81	30	200	5.1	-97	-0.7	+41	-155	-34	0.59
HD 148816	14 8 81	120	100	7.3	-52	2.2	-42	-182	-62	0.70
HD 157089	15 8 81	75	150	7.0	-162	1.7	+153	-51	-54	0.45
HD 157214	14 8 81	35	200	5.4	-78	0.8	-26	-81	-64	0.32
HD 165908	9 8 81	20	300	5.0	+1	1.2	-4	-1	+9	0.08
HD 170153	9 8 81	10	300	3.6	+33	-0.4	+4	+41	-3	0.31
HD 222368	15 8 81	15	500	4.1	+5	1.0	-9	-31	-29	0.09
HD 224930	8 8 81	50	300	5.8	-35	0.4	-9	-74	-34	0.27
HD 225239	9 8 81	45	100	6.1	+4	2.4	-101	-41	-9	0.35

the $3^{m}_{.}6$ CFH telescope (Spite and Spite, 1981) an observation program was undertaken, including some extreme Population II stars (halo stars) and high velocity stars. The reciprocal dispersion of the spectra is about 4.8 Å/mm. The receiver is a Reticon array (Campbell et al., 1981) with 15 µm diodes; the definition (resolution) is about 0.26 Å; in spite of the faintness of even the brightest halo dwarfs, the exposure time was extended up until the obtention of a good signal to noise ratio (Tables 1 and 2). Care was taken of compensating for the variation of sensitivity from diode to diode, using "flat-field" exposures of nearly exactly the same exposure level as the stellar spectrum. Under these circumstances, the equivalent widths of the rather faint lithium resonance line are very accurate, and lines as weak as 4 mÅ can be detected. These observations are briefly described in Spite and Spite (1982) and some spectra are displayed in the Fig. 1.

Moreover, one bright halo dwarf (ν Ind) was observed with the E.S.O. $1^{m}_{.}4$ telescope (CAT), using the coudé (CES) spectrograph with a definition of about 0.1 Å (Maurice et al., 1982). 13 well known halo dwarfs and 9 old disk dwarfs were finally observed and the observational data are presented in Tables 1 and 2. A search in the literature, for the limit between "halo stars" and "old disk stars", shows that this limit has been chosen quite differently by various authors, and often rather arbitrarily. However, Carney (1979) found a discontinuity in the relation $\delta(U-B)$ versus [Fe/H] at about [Fe/H] = −1.0 dex, and we admitted here this limit.

The stars in Table 1 (hereafter called "halo stars") are metal deficient by a factor ranging from 12 to 250 relative to the Sun. The stars in Table 2 (hereafter called "old disk stars") are metal deficient by a factor ranging from 2 to 10.

For helping with the interpretation of the results, we gathered in Table 1 the radial velocity v_r, the computed vectors $\boldsymbol{u}$, $\boldsymbol{v}$, $\boldsymbol{w}$ of the space motion and the eccentricity of the galactic orbit e; when included in Eggen (1964) these data were borrowed from Eggen. Otherwise the computations were made with the formulae of Eggen (1962): the absolute magnitude of the star, and therefore its distance, has then been computed by attributing to the star the absolute magnitude of the star which has the same color index $(B-V)$ in the corresponding standard main sequence: for halo stars it is the globular cluster main sequence as defined by Sandage (1970); for old disk stars it is the main sequence of the solar neighbourhood as defined in Landolt-Börnstein (Schmidt-Kaler, 1982). This procedure provides space velocities and eccentricities which are good enough for illustrating the main features of the kinematical properties of the two samples.

III. Analysis

Most of the stars analysed here are well-known metal deficient stars. Their high dispersion spectra in the blue wavelength range have been previously analysed by one or several authors and the

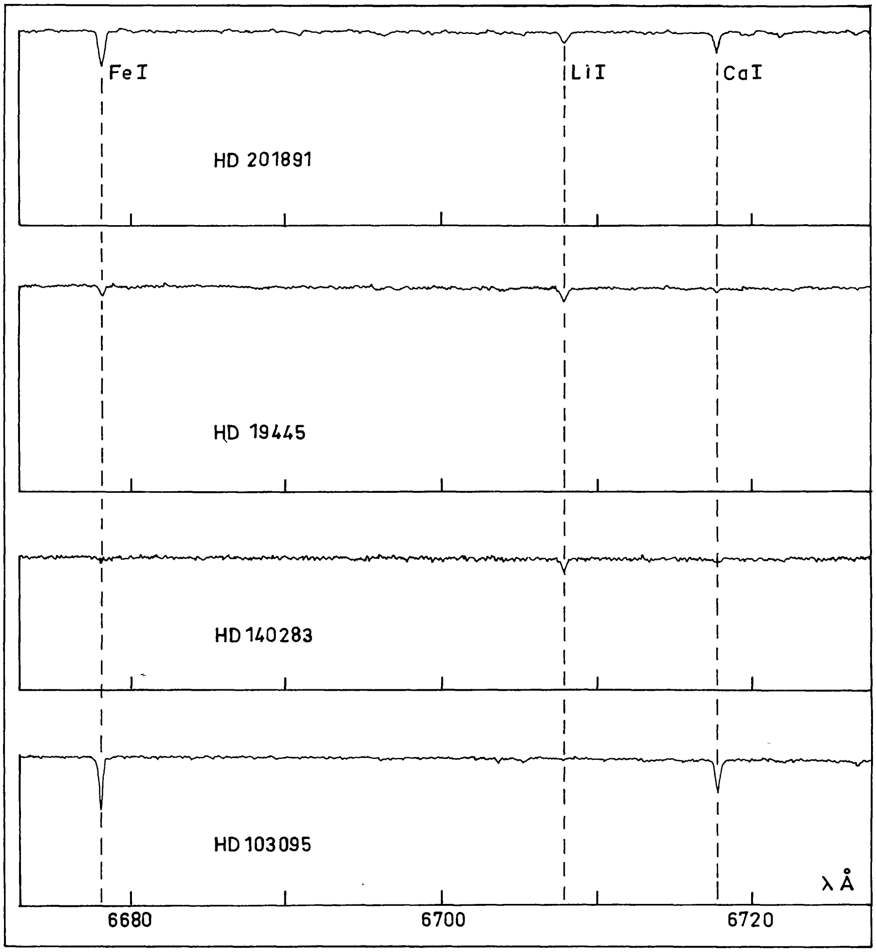

Fig. 1. Spectra of some extreme halo stars

main characteristics of their atmosphere (effective temperature $T_{\rm eff}$, gravity g, and relative metal deficiency [Fe/H] are catalogued by Cayrel et al. (1980). These values are given in Tables 3 and 4 with the precise reference to the author. The model atmosphere have been interpolated in the grid of Peytreman (1970, 1974) and the microturbulent velocity parameter was supposed to be equal to $1\,{\rm km\,s^{-1}}$.

The precise abundance of the high velocity star HD 225239 was up to now unknown. Carney (1982) in its catalogue of field Population II stars quotes for it: $(R-I)_J=0.390$ i.e. from Johnson (1967) $T_{\rm eff}=5480°$ or $\theta_{\rm eff}=0.92$; HD 225239 is a trigonometric subgiant and we estimated $\log g=3.8$. With these values, a model was interpolated in the grid of Peytreman (1970, 1974) and the lines of the spectrum between $\lambda=6600$ Å and $\lambda=6740$ Å were analysed. We obtained $[{\rm Fe/H}]=-0.6$. This value depends very slightly on the gravity. The internal error is very small as it can be seen on the curve of growth of Fe I (Fig. 2).

For all the stars, we computed then the profiles and the equivalent widths of the lithium doublet; we admitted:

$\lambda=6707.761 \quad gf=1 \quad {\rm CH}=6.6\,10^{-33}$

$\lambda=6707.912 \quad gf=0.5 \quad {\rm CH}=6.6\,10^{-33}$,

where gf is the oscillator strength (Wiese et al., 1966) and CH the Van der Waals value of the interaction constant. In these computations we supposed that the abundance of ^{6}Li was negligible: the resolution of the CFHT spectra was not sufficient to determine with precision the ratio $^6{\rm Li}/^7{\rm Li}$, but from the position of the observed line it is clear that anyway, in all the cases, ^{7}Li is highly predominent. An attempt towards a more precise determination of this ratio in some of these stars, from spectra obtained with the CES spectrograph of ESO, is in progress (Maurice et al., 1982). In Tables 3 and 4 are given the equivalent widths of the lithium lines measured on the spectra and the computed abundances of lithium. The error in the determination of this abundance must be small: the lithium lines, indeed, are weak (Fig. 1) and thus, their equivalent widths are a linear function of the abundance of lithium in the photosphere of the star; on the other hand these equivalent widths are well determined because the signal-over-noise ratio of the spectra is generally high and because the continuum is particularly well defined in the red domain of the spectra of metal deficient stars.

The analysis has been made within the LTE hypothesis, because, in the solar atmosphere, the error produced by this approximation amounts to only 5% (Müller et al., 1975) which is negligible here. The error induced by the imperfections of Peytreman's models is not easily estimated, but should not be much greater than 10% and should be approximately the same for all the stars studied.

The value of the lithium abundance is very slightly dependant on the determination of the gravity: an error of 0.5 on $\log g$ corresponds to an error of 4% in the determination of $N_{\rm Li}$. As usual, the main source of error in the determination of the abundance comes from the difficulty in determining a very precise value of the temperature of the stars: we can reasonably admit

Table 3. Lithium abundance in some halo stars

	log T_{eff}	log g	$\left[\frac{Fe}{H}\right]$	Ref.	W_{Li}	log N_{Li}
HD 19445	3.758	4.0	-2.1	(2)	33	2.00
HD 76932	3.768	3.5	-1.1	(5)	23	1.96
HD 84937	3.796	4.0	-2.1	(8)	18	2.05
HD 94028	3.763	4.0	-1.7	(8)	35	2.09
HD 103095	3.711	4.7	-1.4	(4)	<4	<0.5
HD 134169	3.763	3.8	-1.6	(6)	44	2.23
HD 140283	3.739	3.3	-2.4	(2)	45	1.98
BD 20°3603	3.778	4.0	-2.2	(8)	28	2.11
HD 188510	3.724	3.8	-1.8	(6)	18	1.43
HD 194598	3.764	4.0	-1.6	(7)	27	2.00
HD 201891	3.763	4.5	-1.4	(7)	23	1.89
HD 211998	3.716	3.5	-1.5	(3)	13	1.04
HD 219617	3.753	3.9	-1.4	(1)	42	2.10

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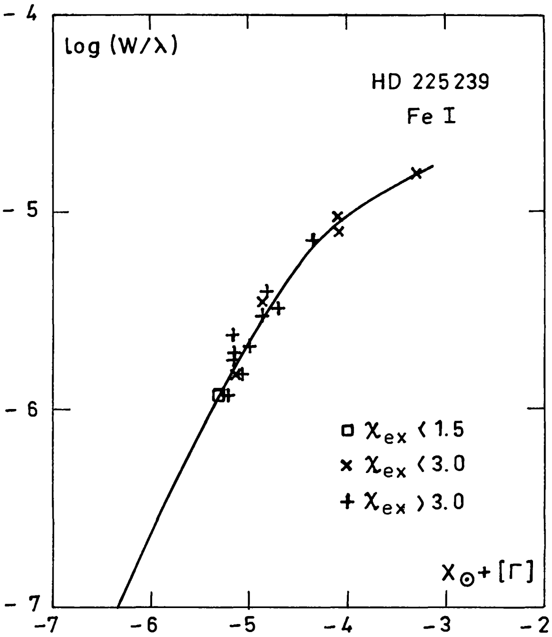

Fig. 2. Curve of growth of Fe I for the old disk star HD 225239

that, for all the stars analysed here, the parameter $\theta_{eff}=5040/T_{eff}$ is known with a precision $\Delta\theta=\pm0.02$ which corresponds to Δ[Li/H] $=\pm0.2$ dex.

To our sample of "old disk stars" we have added four stars taken from the list of Duncan (1981). They are all the stars of this list, which are known to be metal deficient ($-1.0\leqq$[Fe/H]$\leqq -0.3$) from spectroscopic high dispersion study, and which are not yet in Table 4.

Table 4. Lithium abundance in some old disk stars

	log T_{eff}	log g	$\left[\frac{Fe}{H}\right]$	Ref	W_{Li}	log N_{Li}
HD 6582	3.725	4.6	-0.7	(5)	<4	<0.6
HD 148816	3.743	4.0	-0.5	(2)	17	1.53
HD 157089	3.768	3.7	-0.5	(6)	25	2.11
HD157214	3.748	4.2	-0.6	(5)	<4	<0.9
HD 165908	3.778	4.2	-0.4	(4)	41	2.38
HD 170153	3.789	4.3	-0.3	(3)	42	2.52
HD 222368	3.778	3.9	-0.5	(5)	22	2.05
HD 224930	3.716	4.3	-1.0	(5)	<4	<0.5
HD 225239	3.739	3.8	-0.5	(1)	32	1.81

References

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Remark: The particular case of χ Dra

χ Dra is an astrometric and spectroscopic binary (Vinter Hansen, 1942): χ Dra A is an F type star and χ Dra B a K type star (Spite, 1967). When we obtained the red spectrum of χ Dra at the CFHT, the two sets of lines from χ Dra A and χ Dra B were clearly separated. The equivalent width of the lithium line of χ Dra B was less than 3 mÅ. On the contrary the lithium line of χ Dra A was clearly visible and equal to 35 mÅ: but the continuum of χ Dra B, which "veils" the line of χ Dra A, has to be taken into account (Spite, 1967). The final value obtained is: $W_{Li}=42$ mÅ.

IV. Causes of Lithium Alteration in the Atmosphere of the Stars

Does the observed lithium abundance (Tables 3–5) represent the abundance of the prestellar gas?

In all the stars analysed here it is very unlikely that the lithium observed in the atmosphere was produced, even in part, inside the stars themselves, and then transported up into the atmospheres. Such process has been indeed advocated for explaining the large abundance of lithium found in few Li-rich giants and in the weak G band stars (cf. for example Parthasarathy and Kameswara Rao, 1980), but these phenomena occur at a late stage of evolution when the star is far away from the main sequence, and the stars of Tables 3, 4, and 5 are all dwarfs or subgiants.

On the contrary, a part of the lithium of the prestellar gas could have been destroyed during the life of the star: the nucleus of lithium is very fragile and is destroyed by proton fusion as soon as the temperature reaches a few millions of degrees. Two processes have been considered:

the first one is the large convection existing when the protostar reaches the main sequence: Lithium can be drawn into hot central layers where it is destroyed (Bodenheimer, 1965).

Table 5. Lithium abundance of some old disk stars with W_{Li} from Duncan (1981)

	log T_{eff}	log g	[Fe/H]	Ref.	W_{Li}	logN_{Li}
HD 106516	3.783	4.3	-0.40	(1)	<11	<1.8
HD 110897	3.763	4.5	-0.30	(2)	33	2.10
HD 142373	3.763	3.9	-0.30	(2)	69	2.58
HD 216385	3.783	3.9	-0.62	(2)	47	2.53

References

(1) Cayrel de Strobel, G. 1966, Ann.Astr. 29,413

(2) Hearnshaw, J.B. 1974, Astron. Astrophys. 34,263

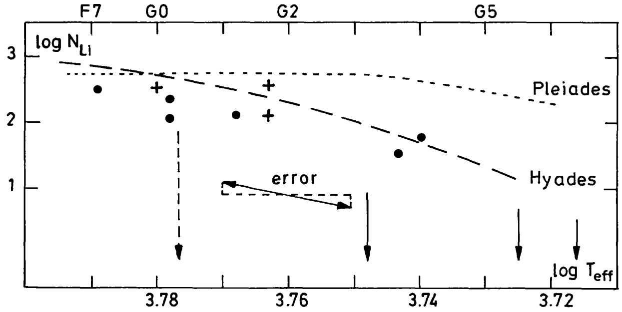

Fig. 3. logN_{Li} versus logT_{eff} for some old disk stars we measured (dots) or measured by Duncan (crosses). The mean curves for the Pleiades (dotted line) and for the Hyades (dashed line) are from Duncan (1981)

The second process is the convection existing in the envelope of the main sequence stars, extended by another process such as overshooting and/or diffusion (Schatzman, 1977; Vauclair et al., 1978).

Both theories predict a decrease of the lithium abundance for the coolest and less massive stars. But in the first case, the destruction of lithium must be independent of the age of the star; on the contrary in the second case, in an old star the stellar convection acting during a longer time has destroyed more lithium than in a young star of the same mass and effective temperature. However in both theories, the amount of lithium really destroyed is very sensitive to the mixing length adopted in computations, value which is not very well known.

The only set of data large enough for a fruitful confrontation between theories and observations is the set of data accumulated for Population I stars.

A. Comparison of Lithium-destruction with Observations in Population I Stars

The general picture of Li destruction in Population I stars is rather confusing, and in order to clarify the following discussion we will first state the conclusions to which we were lead by a careful analysis of Duncan's data combined with ours.

1. The graph log N_{Li} versus log T_{eff} for the Pleiades (Fig. 3 dotted line, from Duncan 1981) rules out a significan proto-stellar destruction of lithium in the $1 M_\odot$ stars (Bodenheimer 1965); generalizing this fact we propose to always neglect the protostellar destruction of lithium in the $1 M_\odot$ stars.

2. The shape of the same diagram for the Hyades (Fig. 3 dashed line, from Duncan 1981) shows a progressive destruction of lithium, larger when the temperature (and the mass) is lower; we attribute this progressive destruction to the action of the convective envelope (extended by other processes such as overshooting and/or diffusion or turbulent transport) in the main sequence phase.

3. The position of the old Population I stars (slightly metal poor stars with high velocity) shows that the abundance of lithium in this type of stars is approximately the same at the same temperature, as in the Hyades. Since the destruction process could act during a longer time, this suggests that the larger duration must be compensated by a lower efficiency of the process (smaller depth of the convective zone).

4. Duncan (1981) measured the lithium abundance in a set of young (Population I) dwarfs. Among the G dwarfs:

More than a half have a lithium abundance not very different from the abundance of the Hyades.

Less than a half have little or no lithium, like the Sun.

The repartition of the ages is statistically the same in both subsets, and the mean age is about the solar age.

As a consequence the Sun is not perfectly representative of the "Population I G dwarfs".

Moreover the lithium destruction has been more efficient in the "lithium poor group stars" than in the "lithium rich group stars". Since the metallicity and the age of the two groups is the same, another process has to play a role: for example a process induced by rotation.

Discussion

A.1. The Pleiades. Duncan (1981) observed a large set of stars in the two young clusters: the Pleiades and the Hyades. The Pleiades are so young (their age is 0.08 ($\pm$0.015) 10^9 yr following Patenaude, 1978) that they are a good laboratory to test the quantity of lithium destroyed in the protostellar phase. When, for the stars of this cluster, the lithium abundance logN_{Li} is plotted versus the temperature logT_{eff}, logN_{Li} seems constant, inside the errors, down to at least logT_{eff}=3.74 (Fig. 3 dotted line). This does not confirm the theory of Bodenheimer which predicts that practically no lithium is destroyed in hot F dwarfs but that half of the lithium is destroyed in $1 M_\odot$ star (logT_{eff}=3.76). Let us recall however that the amount of lithium is in fact very sensitive to the mixing length adopted in the computations.

Unfortunately, in the graph of the Pleiades the dispersion of the dots is quite large (cf. Duncan, 1981); recent observations of the Hyades by G. and R. Cayrel at the CFH telescope show that more accurate measurements of Li abundance lead to a smaller dispersion in the graph logN_{Li} versus logT_{eff} (Cayrel et al., 1981). We thus hope that similar observations of the Pleiades in the future will permit a more precise determination of the quantity of lithium really destroyed in the protostellar phase. Until more precise determination, we propose to assume that the protostellar destruction of lithium can be neglected in $1 M_\odot$ stars.

A.2. The Hyades. The age of the Hyades is approximately 0.7 $\pm$0.15 b.y. (Patenaude, 1978; Hirshfeld, 1980). The curve logN_{Li} versus temperature in the Hyades (Fig. 3 dashed line) shows a decrease of the abundance of lithium for the coolest and less massive stars. The difference between the mean curve of the Hyades and of the Pleiades (Fig. 3) would give a measurement of lithium depletion in approximately 10^9 yr; depletion that we attribute to a destruction by the action of the convection (extended by processes such as overshooting, turbulent transport and or diffusion) in the envelope of the main sequence stars.

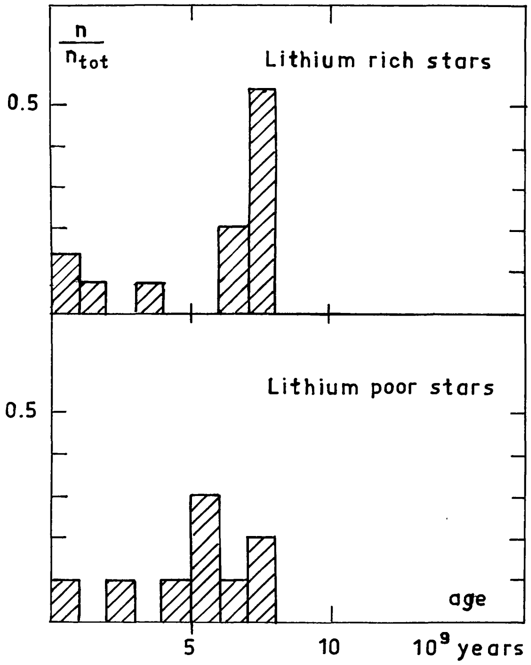

Fig. 4. Histogram: number of stars versus age for Pop I stars with a normal metal abundance and $\log T_{\rm eff} = \log T_{\rm eff\odot}$. The stars are taken from Duncan (1981) and their ages are computed from the absolute magnitude by the method used by Perrin et al. (1977). The stars are divided in two groups: lithium rich stars and lithium poor stars. It can be seen that in both samples the repartition of the ages is similar

A.3. The Old Population I Stars. It is interesting to compare the behaviour of the young stars in the Hyades with the old Population I stars we observed. In Table 4 and 5 are gathered stars which are metal deficient by a factor ranging from 2 to 10 and which have generally high velocities, two characteristics of the old stars. They are statistically at least, older than the Sun, their ages can be estimated as clustering around $10\,10^9$ yr. After the comparison between the Pleiades and the Hyades it was expected that, in old Population I stars, lithium is depleted more than in the Hyades; and since convection is more efficient in low mass stars than in large mass stars, it is expected also that the differences is larger in the G stars ($\log T_{\rm eff} < 3.77$) than in the F stars ($\log T_{\rm eff} > 3.77$). In fact (Fig. 3) this is not the case: at the same temperature the abundance of lithium is approximately the same in the atmosphere of the old disk stars and in the Hyades. Marginally it seems that the abundance of lithium of the old disk stars of type F is lower than in the Hyades while the G stars are similar; (the contrary of what could be expected from the effect of the convection).

What is the explanation of this phenomenon? Is the slight metal deficiency of the old disk stars able to reduce sufficiently the depth of the convective zone (cf. B in this chapter)? If we take this as a tentative hypothesis, the smaller slope of the graph $N_{\rm Li}$ versus $\log T_{\rm eff}$ for the old disk stars is explained. On the other hand the fact that the old disk stars of type F have a lower lithium abundance than in the Hyades would indicate that the prestellar material which formed these stars is poorer in lithium than the young interstellar matter. [Another possibility would be a larger difference of the gravitational sorting of lithium (Vauclair et al., 1978) between F and G stars.] But since this effect is not seen in Population II stars (cf. B) we will not retain this explanation. From Fig. 3, we could estimate that $10\,10^9$ yr ago, $\log N_{\rm Li} = 2.5$ in the scale $\log N_{\rm H} = 12$.

A.4. The Young Population I Stars. The Sun is approximately $5\,10^9$ yr old, and it is well known that there is practically no lithium in its atmosphere. The solar abundance of lithium has been used by Duncan (1981) to deduce a relation age – lithium abundance by comparison with the Pleiades and the Hyades.

In fact the Sun is probably not a good representative of the solar-age-G-dwarfs and, as a consequence, the relation deduced by Duncan is generally not correct.

We selected in the Table I of Duncan all the stars with normal metallicity and with $3.77 \leqq \log T_{\rm eff} \leqq 3.76$ (the solar value is 3.763). There are 25 stars in this interval of temperature. Among these stars only 10 stars have an undetectable lithium line like the Sun (lithium poor group). In the other 15 stars the lithium abundance can be measured (lithium rich group); the mean value of the lithium abundance is $\log N_{\rm Li} = 2.35$ a value very similar to that of the Hyades having the same temperature.

The parallaxes of all the selected stars is known with a reasonable precision, thus the absolute magnitudes of the stars and then their ages can be estimated using the method of Perrin et al. (1977) based on the evolutionary tracks of Hejlesen (1980). Since the age of the Sun is slightly overestimated in these theoretical diagrams, the ages were estimated relative to the Sun. The precision of this determination is not very high but it is sufficient to suggest that:

a) The repartition of the ages (Fig. 4) is not significantly different in the lithium rich group and in the lithium poor group of stars. The lithium rich stars are not statistically younger than the lithium poor stars.

b) In both groups the "mean age" is approximately the age of the Sun. Thus the lithium rich stars are not as young as the Hyades (Fig. 4).

A problem now arises: it seems that it exists two types of stars. In one type (Hyades, lithium poor G dwarfs) the depletion process seems very efficient, in the other type the depletion process seems to act more slightly (lithium rich G dwarfs, old disk stars). This suggests that another mechanism occurs sometimes which accelerates the lithium destruction; for example an initially high rotational velocity of the star would favour more Li destruction. Let us recall that the Hyades have a rather large mean stellar rotation and are metal rich (Cayrel et al., 1982).

The problem of lithium destruction in Population I stars is not definitively resolved here. Detailed computations of the convective zone in stars with different metallicity could help to understand the phenomena which govern lithium destruction.

B. Lithium in the Old Population II Dwarfs

In Fig. 5, $\log N_{\rm Li}$ is plotted versus $\log T_{\rm eff}$ for 13 classical extreme halo dwarfs; all these stars are very old, their metal abundance is very low (Table 3) and their space velocity is high (Table 1). It is generally admitted that these stars were formed at the very beginning of the Galaxy, and their age can be estimated as about $15\,10^9$ yr. The dispersion of the dots in Fig. 5 is very small. The abundance of lithium seems constant between $\log T_{\rm eff} = 3.796$ and $\log T_{\rm eff} = 3.74$: in this interval the mean value is $\log N_{\rm Li} = 2.05$ (for $\log N_{\rm H} = 12$) Only for the coolest stars, the abundance of lithium in the stellar atmosphere goes down.

Clearly the size of the sample of studied Population II dwarfs is small (13 stars), but only a few bright Population II dwarfs are

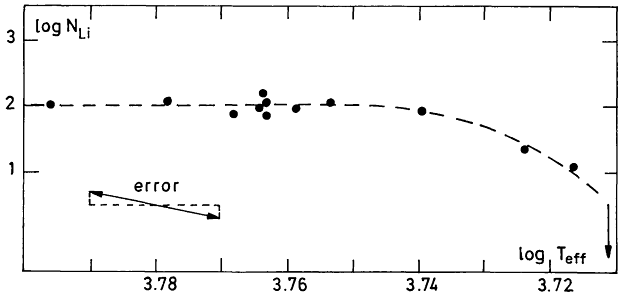

Fig. 5. N_{Li} versus $\log T_{eff}$ for old halo stars

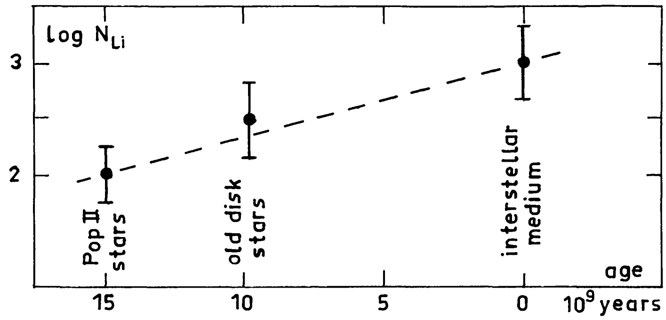

Fig. 6. Evolution of the Li abundance during the life of the Galaxy

known, and it is not easy to increase strongly this sample in a near future unless more powerful devices become available. In particular it is not possible to observe Population II dwarfs hotter than $\log T_{eff} = 3.80$, since hotter stars are evolved (turn-off limit).

Figure 5 suggests that lithium is not destroyed by convection in solar type stars of Population II, which are long known to be typically slow rotators. A crude theoretical prediction would indicate that a large metal deficiency implicates a reduced opacity and therefore a stellar convective zone of reduced depth. Recent computations of Däppen and Maeder reported by Cayrel (Däppen, 1982) seem to show a large depth reduction of the convective zone. This explains that the convection (even extended by other processes) cannot drive lithium deep enough to encounter temperatures high enough ($2.5\,10^6$ K) for inducing lithium destruction.

Since pre-main sequence destruction of lithium seems negligible in the young Population I stars (*A*-1) we will admit that it is negligible also in the old Population II stars. If we suppose therefore that neither protostellar nor convective main-sequence Li destruction occur in halo dwarfs with $\log T_{eff} > 3.74$ then we would expect that the curve $\log N_{Li}$ versus $\log T_{eff}$ is an horizontal line until $\log T_{eff} = 3.74$, in agreement with Fig. 5.

Mass loss by stellar winds could also deplete the lithium in the external layers of stars (Reeves, 1982), especially in the case of old stars where this process could take place for a long time. But no detailed calculations are available now, and it would be expected that the corresponding Li-depletion would be mass dependent (and/or temperature dependent): here again Fig. 5 does not favour such an hypothesis. It is very unlikely that the lithium observed in Population II stars has its origin, even in part in the matter which would be accreted from young interstellar clouds. It is true that these old stars have crossed numerous interstellar clouds, but they have (Table 1) large spatial velocities and it is known (McCrea, 1953) that under these circumstances the accretion mechanism is largely inefficient. Let us point out that moreover, the computations of McCrea do not take into account the stellar wind.

Keeping in mind the present uncertainties until the final discussion, we will admit that no depletion nor accretion of ^{7}Li took place in the formation and evolution of the hottest halo dwarfs. Then, the lithium abundance defined by the "plateau" of the curve $\log N_{Li}$ versus $\log T_{eff}$, represents the lithium abundance which existed in the matter which formed the star, i.e. the abundance of lithium in the interstellar matter at the very beginning of the Galaxy $15\,10^9$ yr ago. This abundance was $\log N_{Li} = 2.05$ or $N_{Li} = 11.2\,10^{-11}\,N_H$.

As previously noted in Sect. III (Analysis), the error of the determination of the abundance of lithium in one star may be estimated as 0.2 dex. The limited scatter in abundances (Fig. 5 and Table 3) suggests that the hot Population II stars could have the same abundance of lithium, and that the observed dispersion could be entirely due to the errors in the individual determination of the abundance. An elementary statistical analysis shows that this could be indeed the case. More conservatively let us note that the determined abundances are clustering around $\log N_{Li} = 2.05$ with a range of very nearly ± 0.15. As a consequence we will admit that the abundance of lithium at the beginning of the Galaxy was: $N_{Li} = 11.2\,(\pm 3.8)\,10^{-11}\,N_H$.

V. Evolution of the Lithium Abundance in the Galaxy

The main results of this work can be summarized in a graph of the abundance of lithium in the Galaxy versus time (Fig. 6). It is clear that these estimations of the abundance of lithium at given epochs cannot be considered as definitive, the error bars are large, but it seems that the Galaxy has been enriched in lithium more or less regularly. Lithium is now ten times more abundant than it was in the early Galaxy.

A problem is to determine what process strongly enriched the Galaxy in lithium. At the present time the answer to this question is not clear. Spallation alone must be ruled out because it would form too large a quantity of beryllium and boron. The production of lithium in novae can be advocated but the theoretical computations must be done. Some other processes can be found, such as formation in stars in advanced phases of evolution (Lambert and Dominy, 1980 and references therein; Parthasarathy and Kameswara Rao, 1980). It would be important anyhow to measure the abundance of Beryllium and of Boron in the brightest old disk stars: an important check to these processes are the ratios Be/Li, B/Li, and ^{6}Li/^{7}Li since some processes which synthesize ^{7}Li could be able to synthesize also ^{6}Li, Be, and B.

VI. Cosmological Consequences of the Measurement of the Lithium Abundance at the Beginning of the Life of the Galaxy

1. Does the Measured Abundance of Lithium Represent the Primordial Value?

Although our observations suggest a more or less continuous enrichment of ^{7}Li during the life of the Galaxy, at least some ^{7}Li was existing at the very first ages of the Galaxy (Fig. 5). Since the standard model of the Big bang (Wagoner, 1973; Olive et al., 1981) predicts the production of light elements, and especially ^{7}Li, it is likely that the origin of the lithium existing at the first ages of the Galaxy was produced in the Big Bang.

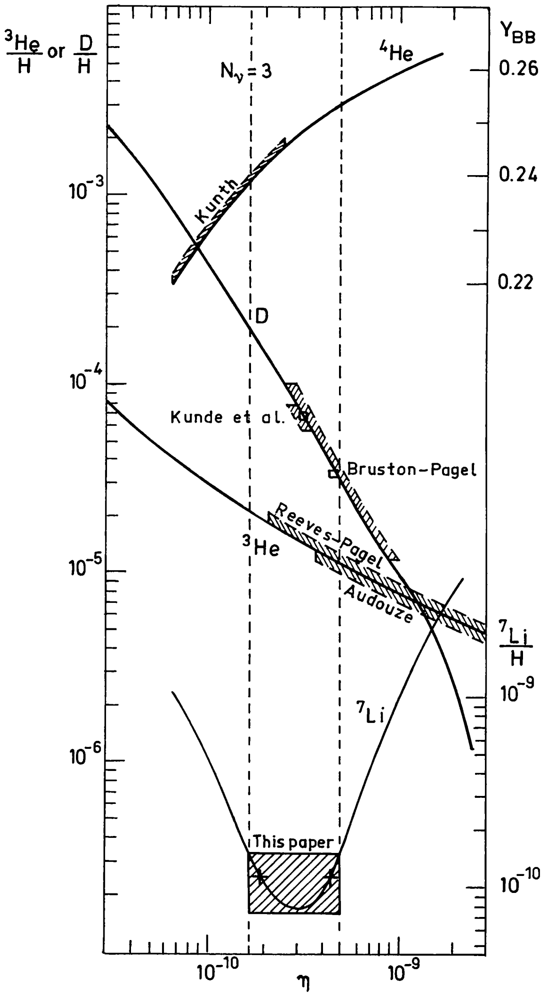

Fig. 7. D, ^{3}He, ^{7}Li by number and primordial ^{4}He by mass (Y_{BB}) versus the ratio of baryons to photons in the Universe. The theoretical curves are from Schramm (1982). Our determination of Li/H and the determinations of Y_{BB}, D/H, ^{3}He/H from different authors are plotted on the diagram

However, several processes could take place between the nucleosynthesis of ^{7}Li and the formation of halo dwarfs: perhaps some Li could be destroyed or produced and we have to evaluate the influence of these processes in order to ascertain if the primordial abundance has been significantly altered or not.

Before the formation of the halo stars, the galactic matter indeed was processed in supernovae, which simultaneously destroyed lithium and produced heavy elements. But the halo stars have a very small content of heavy elements, so that the proportion of astrated material mixed with the primordial material is very small, and the corresponding alteration of Li abundance completely negligible. Moreover the abundance of lithium is independent of the iron abundance (Table 3).

Other processes could be considered in principle:

(i) A large burst of cosmic rays could produce a part of the lithium observed in the halo stars. But the target nuclei (such as CNO) were scarce in the interstellar matter, and this production should be negligible: otherwise the ratios ^{6}Li/^{7}Li, Be/Li, and B/Li would be different from the observed ones in Populations I objects (Audouze, 1981). In particular, this spallation would lead to a high ratio ^{6}Li/^{7}Li which is not observed in halo dwarfs (Maurice et al., 1982).

(ii) It has been suggested that ^{7}Li could be built in novae (Starrfield et al., 1979; Vigroux and Arnould, 1980). However this mechanism has a long time-scale; so that it is unlikely that it were able to provide a significant amount of ^{7}Li in the extreme halo stars which must be almost as old as the Galaxy itself.

(iii) Another possible source of ^{7}Li could be the production by Super-Massive objects (Nørgaard and Fricke, 1976); here the evolution time is very short, but, up to now the existence of such a type of object has not been proven.

Finally we consider that the most likely hypothesis is that the observed lithium in extreme Population II dwarfs existed in the material from which the Galaxy was formed. Between the production of ^{7}Li in the Big Bang and the formation of halo dwarfs, no significant production of ^{7}Li is likely. The observed Li abundance is thus at least, a lower limit of the ^{7}Li produced by the Big Bang.

Pending confirmation by more numerous observations, no process of Li destruction seems very likely, although, admittedly our sample of Population II stars is small. Therefore we consider that the most probable estimation of the abundance of ^{7}Li produced by the Big Bang is the abundance measured in halo dwarf stars: $N_{Li}/N_H = 11.2\ (\pm 3.8)\, 10^{-11}$. Naturally the error quoted takes only in account the random error on the "plateau" of Fig. 5.

2. *Constraints on the Model of Big Bang*

Previous estimations of the ^{7}Li abundance produced by the Big Bang amounted to larger values: The mean value observed in Population I objects is $N_{Li}/N_H = 9.2\, 10^{-10}$ and it was up to now admitted that the lithium enrichment during the life of the Galaxy was small (models of Meneguzzi et al., 1971). Therefore, the Big Bang was estimated to produce approximately $N_{Li}/N_H = 8\, 10^{-10}$ (Boesgaard, 1976).

When compared to the predictions of the model of Wagoner (1973), this value led to a mean baryonic density $\varrho_b = 8\, 10^{-31}$ g/cm^3. Our new estimation of the production of ^{7}Li in the Big Bang leads, when the standard model of Wagoner is adopted, to a value clearly lower than the preceding estimation: $\varrho_b < 2.7\, 10^{-31}$ g/cm^3. Anyhow, given that the Universe is a Friedmann universe with zero cosmological constant, all the determinations of the mean baryonic density ϱ_b support the conclusion that the Universe cannot be closed by nucleons.

However in the model of Wagoner (1973), it was supposed that there were only two types of neutrinos. Now three different types of neutrinos are known and thus the model of Wagoner must be revisited (Yang et al., 1979; Olive et al., 1981; Schramm, 1982). Moreover the newest available model (Schramm, 1982) uses new values of nuclear reactions constants; among few differences with Wagoner's model, the production of lithium by the Big Bang is increased by a factor of about 2. As shown in Fig. 7, this new model predicts the amount of D, ^{3}He, ^{4}He, and ^{7}Li which have been synthesized during the Big Bang as a function of η the ratio of the number of baryons to photons in the Universe. It is interesting to discuss the mutual consistency of the predicted and observed abundances.

Lithium

Our determination corresponds approximately to the minimum of the theoretical curve and leads to a rather low value of η:

$1.6\,10^{-10} \leqq \eta \leqq 5\,10^{-10}$. These limits are drawn on Fig. 7, and correspond to $\varrho_b \leqq 3.3\,10^{-31}$ or $\Omega h^2 \leqq 0.02$.

Deuterium

Bruston et al. (1981) show that in the nearby interstellar matter the D/H ratio should be approximately $2.5\,10^{-5}$. This value has been corrected for astration by Pagel (1982) to estimate the pregalactic value. He obtains then: $N_D/N_H = 3.3\,10^{-5}$ with an uncertainty by a factor of about three. Recently Kunde et al. (1982) proposed a value of N_D/N_H extrapolated back in time from measurements in Jupiter and leading to $6\,10^{-5} \leqq N_D/N_H \leqq 8\,10^{-5}$ in the case of a no-infall galactic model (Audouze and Tinsley, 1972). These two determinations are consistent with our determination of lithium abundance; a better agreement is obtained with the value of Kunde et al. (Fig. 7).

^{3}He

The evaluation of the primordial ^{3}He abundance seems very uncertain. Pagel (1982) suggests that the proto-solar abundance $N_{^3He}/N_H = 1.8\,10^{-5}$ (Reeves, 1974) must be considered as an upper limit of the primordial value. Audouze (1981) even proposes $0.4\,10^{-5} \leqq N_{^3He}/N_H \leqq 1.3\,10^{-5}$ but it seems from Fig. 7 that the higher value is more probable.

^{4}He

Kunth (1981a, b) recently determined the helium abundance in 13 unevolved low-luminosity galaxies. The helium abundance by mass in these galaxies ranges from $Y = 0.23$ to $Y = 0.27$, and seems independent of the metallicity Z. Thus Kunth admits that the straight mean of these helium abundances is an upper limit of the amount of ^{4}He built during the Big Bang. He deduces $Y_{\text{Big Bang}} \leqq 0.245$. This upper limit is consistent with the abundance of lithium given in this paper (Fig. 7).

It is encouraging to note that within determination errors the predictions of Schramm (1982) are in agreement with observations. This agreement is however at the limit for ^{4}He, in the case of the three neutrino *flavours* considered here, and the discovery of a new additional type of neutrinos would show a gap between the observations and the predictions of the standard Big Bang model as it is computed at present.

VII. Conclusion

Using material of high quality, the abundance of lithium has been measured with care in the atmospheres of a few extreme Population II dwarfs. Although the number of analysed stars is limited their behaviour is compared to the behaviour of old Population I stars; and also to the behaviour of young Population I stars mainly observed by Duncan.

From these comparisons it results that the most likely interpretation of the data is the following:

1. No significant destruction of ^{7}Li takes places during the protostellar phase for stars of about $1\,M_\odot$.

2. The Li destruction in the cool stars is mainly induced by stellar convection on the main sequence. Convection is extended by some other process (for example overshooting, turbulent diffusion...). The Li destruction rate increases when the convection depth increases, i.e. when the temperature (and the mass) decreases. Sometimes the efficiency of Li destruction is enhanced (by, for example, a rapid rotation of the star?). This could be the case for the Sun which is relatively exceptional among field G stars.

3. The initial lithium abundance of old disk stars seems to be about $\log N_{Li} = 2.5$ (in the $\log N_H = 12$ scale) i.e. $N_{Li}/N_H = 3\,10^{-9}$. In the halo stars (extreme Population II) a well defined value is found $\log N_{Li} = 2.05 \pm 0.15$ which corresponds to $N_{Li}/N_H = 11.2$ $(\pm 3.8)\,10^{-11}$.

4. A mechanism thus exists which enrich the Galaxy in ^{7}Li during its life: the abundance of lithium is ten times higher in the young Population I objects than in the old halo stars; this mechanism cannot be spallation alone, because such a production of ^{7}Li implicates a production of ^{6}Li, Be, and B which is too large to be fitted to observations. The production of ^{7}Li by novae is a likely candidate.

5. Finally the lithium abundance of the old halo stars must be representative of the abundance in the primordial matter.

This abundance constrains the hot Big Bang model (Schramm, 1982) with three neutrino flavours to a baryon to photon ratio: $\eta \leqq 5\,10^{-10}$ i.e. $\varrho_b \leqq 3.3\,10^{-31}$ or $\Omega h^2 \leqq 0.02$. This is in agreement, within the determination errors, with the values predicted by the same model from the abundance of Deuterium and ^{3}He (elements which are formed by rather similar processes). However some estimations, often accepted, of the quantity of ^{4}He built by the Big Bang, such as the estimation of Pagel (1982) $Y_{BB} = 0.23$, do not lead to an excellent agreement neither with Deuterium, ^{3}He, nor Lithium. Using the standard model, a fair agreement can be obtained only for a value of Helium abundance significantly higher than 0.23.

Finally assuming that the Universe is a Friedmann universe with zero cosmological constant, all data converge towards the fact that nucleons cannot close the Universe. However, even assuming $\Lambda = 0$, it cannot be concluded that the Universe is open and will continue to expand forever, before considering at least another alternative: if the neutrinos are massive they could close the Universe.

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Note added in proof: The signal to noise ratios indicated in Tables 1 and 2 are half of the usual S/N ratios (they correspond to the 2σ level).

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