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Very low upper limits on the strength of interstellar lithium lines toward SN 1987 A *

D. Baade[1] **and P. Magain**[2]

[1] Space Telescope-European Coordinating Facility, European Southern Observatory, Karl-Schwarzschild-Strasse 2, D-8046 Garching, Federal Republic of Germany
[2] European Southern Observatory, Casilla 19001, Santiago 19, Chile

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Summary. Seven CCD and eleven Reticon spectra of high spectral resolution and low noise have been carefully analysed in search for faint absorption lines due to neutral interstellar lithium λ 6708 Å along the line of sight to SN 1987 A in the Large Magellanic Cloud (LMC). At the velocities of the strongest interstellar Ca II and Na I lines, no evidence of any interstellar feature has been found. An upper limit for the strongest components expected is 0.15 mÅ for both the Galaxy and and the LMC. From these we infer elemental column densities $N_{\rm Galaxy} \leqq 2.6\ 10^{11}\,{\rm cm}^{-2}$ and $N_{\rm LMC} \leqq 1.4\ 10^{11}\,{\rm cm}^{-2}$ and gaseous elemental abundances $({\rm Li/H\,I})_{\rm Galaxy} \leqq 7.7\ 10^{-10}$ and $({\rm Li/H\,I})_{\rm LMC} \leqq 1.0\ 10^{-10}$ with an estimated uncertainty of the abundance limits of a factor of 4 (0.6 dex).

Key words: interstellar matter – Large Magellanic Cloud – lithium – primordial nucleosynthesis

1. Introduction

Standard big bang models (Yang et al., 1984; Beaudet and Reeves, 1984; Kurki-Suonio and Matzner, 1985; Reeves, 1986a) predict an abundance of ^{7}Li (by number relative to hydrogen) on the order of 10^{-10} to 10^{-9}. Although lithium is not involved in the nuclear burning in normal stars, observations have not until rather recently (see Sect. 4.3) contributed further constraints of the theoretical models because on the one hand lithium is destroyed at temperatures of a few 10^6 K and on the other it is produced by high-energy spallation processes in the interstellar medium (Reeves, 1986b), nova outbursts and the envelopes of red giants (Cameron and Fowler, 1971). As the various processes affect the isotopes ^{6}Li and ^{7}Li differently (Audouze et al., 1983; Reeves, 1986b, c), their relative contribution may in principle be deduced from observations of the ^{6}Li/^{7}Li isotope ratio. However, as Audouze et al. (1983) and Reeves (1986b) discuss, the difference between the rather uniform solar system value of $^6{\rm Li}/^7{\rm Li} \approx 0.08$ (Nichiporuk 1971 and references therein) and the only measurement external to the solar system, namely $^6{\rm Li}/^7{\rm Li} \approx 0.025$ in the interstellar medium toward ζ Oph (Ferlet and Dennefeld, 1984), is difficult to account for. Upper limits of mostly $\leqq 0.1$ have been derived for various F and G stars (e.g. Andersen et al., 1984; Maurice et al., 1984; Rebolo et al., 1986; Pallavacini et al., 1987). The detection and precise measurement of lithium also in external galaxies is therefore of considerable interest, especially if their evolutionary history and state are different from the case of our own Galaxy.

With a metal deficiency of roughly a factor of 3–4 (see, e.g., Dufour, 1983), the Large Magellanic Cloud (LMC) provides for such an interesting comparison, and SN 1987 A (Shelton, 1987) offered the at this time unique opportunity to actually carry it out. From a possible positive detection Vidal-Madjar et al. (1987) have already tentatively suggested that in the interstellar medium of the LMC lithium may be underabundant by a factor of 2. Our subsequent repetition of the observations – although at somewhat lower resolving power ($\geqq$60,000 vs. 100,000) and with a CCD as the detector – did not confirm the reported detection (Fig. 1). The high-frequency signal-to-noise (S/N) ratio is at least comparable to the one of the data available to Vidal-Madjar et al. (1987). But it may be formally objected that residual fringing precludes a naegative result to be arrived at with certainty, although most of the fringes are too wide to be confused with single interstellar lines. In order to finally resolve this conflict, a third series of spectra was obtained with the same instrumentation as used by Vidal-Madjar et al. These data and their analysis are described below.

2. Observations

The set of CCD spectra mentioned in the Introduction of the region around the Li I doublet $\lambda\lambda$ 6707.76, 6707.91 Å (^{7}Li; 6707.92, 6708.07 Å for ^{6}Li) was taken in early April with ESO's Coudé Echelle Spectrometer (CES) fed by the 1.4 m Coudé Auxiliary Telescope (CAT). The so-called short camera of the CES provided a resolving power in excess of 60,000 on an RCA double density chip with 15 μm pixels. Exposures up to near the limit of the A/D converter for the unbinned chip took a few minutes. Division by spectra obtained on a white light source could not perfectly remove the fringes from the images so that the exposures were made at three different grating angles. The wavelength calibration obtained from observations of a thorium arc was better than $200\,{\rm m\,s^{-1}}$ internally and $1\,{\rm km\,s^{-1}}$ externally.

Send offprint requests to: D. Baade

* Based on observations collected at the European Southern Observatory, La Silla, Chile

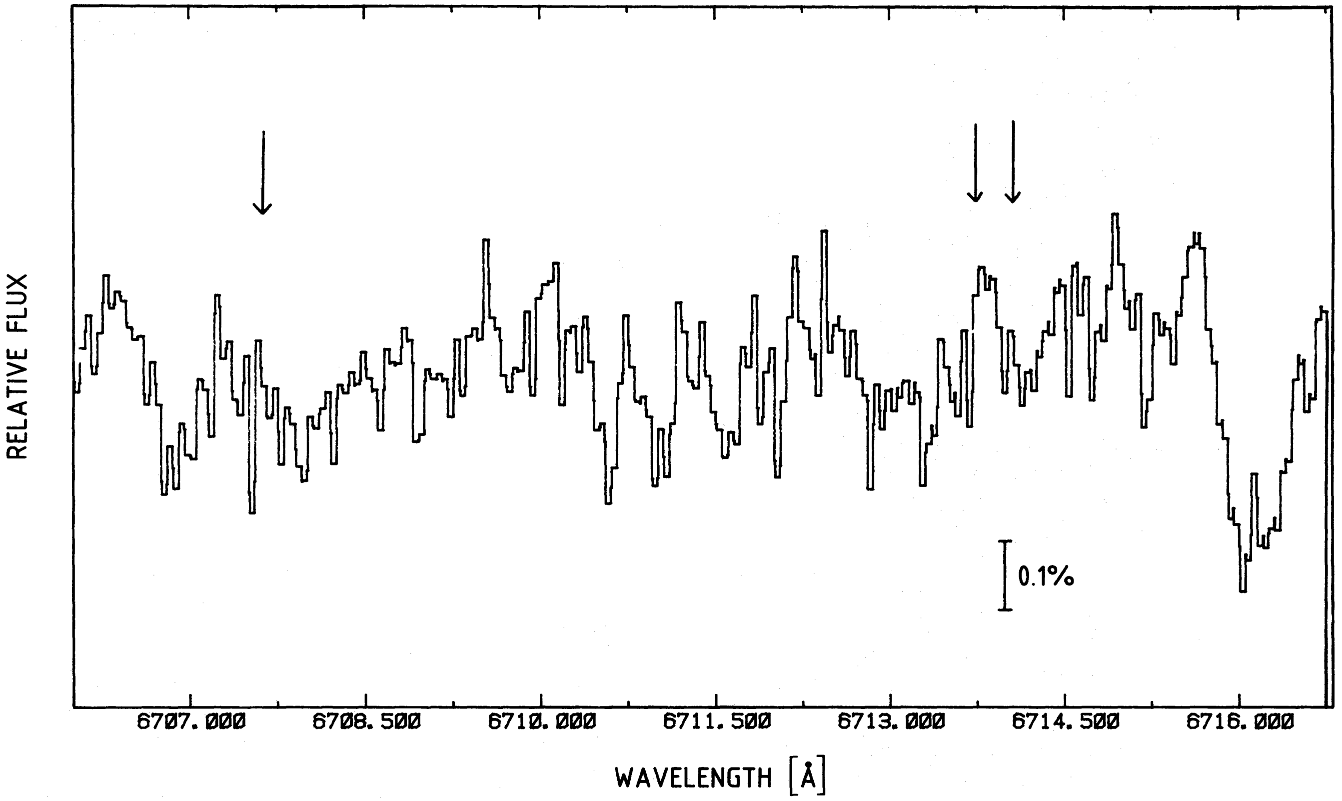

Fig. 1. The spectrum of SN 1987A around λ6710 Å as observed with the CES, Short Camera, and CCD at a resolving power of $\geqq$60,000; a total of 15 spectra obtained at three different grating settings have been averaged. Note the high S/N per pixel but also the modulation at intermediate spatial wavelengths due to imperfectly flatfielded fringing effects in the CCD. Arrows indicate the positions of features attributed by Vidal-Madjar et al. (1987) to interstellar lithium. In order to facilitate the comparison, we have chosen the same scaling as in Vidal-Madjar et al.'s Fig. 2; the flux scale in units of the adjacent pseudo continuum is indicated by the vertical bar in the lower right corner

Another eleven spectra were obtained with CAT and CES in mid-April 1987, however with the long camera of the CES, and with a 1870-diode Reticon array as the detector. This detector does not suffer from fringing and at high flux levels has better S/N properties than current CCDs have (Walker, 1987). Our observations were obtained at a higher incident flux level than were those by Vidal-Madjar et al. (1987) because the resolving power, defined by the entrance slit width of the spectrograph, was set set to 80,000 rather than 100,000, and the continuum brightness of the supernova in the red part of the spectrum and the strength of the Hα emission (in the red wing of which the lithium lines were situated) had risen meanwhile. As a result, the mean integration time was reduced from about one hour at the time of the observations by Vidal-Madjar et al. (1987) to just over 20 min. Experience has shown that for exposures to the same signal produced in the Reticon, spectra obtained within shorter integration times tend to have the better S/N characteristics. Together with the larger number of spectra (11 vs. 6) this should allow for a more precise measurement of interstellar lithium lines than was possible to Vidal-Madjar et al. (1987).

In order to discriminate against residual blemishes in the flat field, the observations were obtained with five different settings of the grating. Ten integrations each on a white light source (for flat fielding) and the fixed-pattern read-out noise were obtained before and/or after every observation of the supernova. The wavelength reference was again provided by a thorium arc lamp (internal accuracy: $\leqq 100\,\mathrm{m\,s^{-1}}$). Care has been taken to calibrate the dark signal of the Reticon as a function of the level of and the time elapsed since the respective previous exposure. The residual uncertainty should be less than 0.3% of the pseudo-continuum flux in our well exposed spectra.

3. Data reduction and analysis

Figure 2 shows nightly averages of the Reticon observations obtained at one and the same grating angle (for the mean CCD spectrum see Fig. 1). They have been corrected in the conventional way for the fixed-pattern read-out noise, dark signal, and response non-uniformity, but the identity of the individual diodes has been retained in order to visualize and locate residual flat-field related blemishes. The occurrence of substantial defects near the center of the array became apparent in the second night. Unfortunately, the additional tilt of the grating applied in the third night was not sufficient to shift the expected Galactic component to a "clean" region of the flat field so that only the last two nights are suitable to search for the Galactic component. This can easily be seen from Fig. 3 where the same data are displayed as in Fig. 2 except for their alignment in heliocentric velocity rather than in pixel space. It is also evident from this figure that any components at the redshift of the LMC were in all five nights at locations without flat field blemishes. The S/N is considerably better in Fig. 3 than in Fig. 2 because we have applied a fast Fourier transform (before the rebinning to constant step in velocity) in order to detect and remove periodic ripples with various periods which are known (Baade 1985, unpublished) to plague data obtained with this Reticon system.

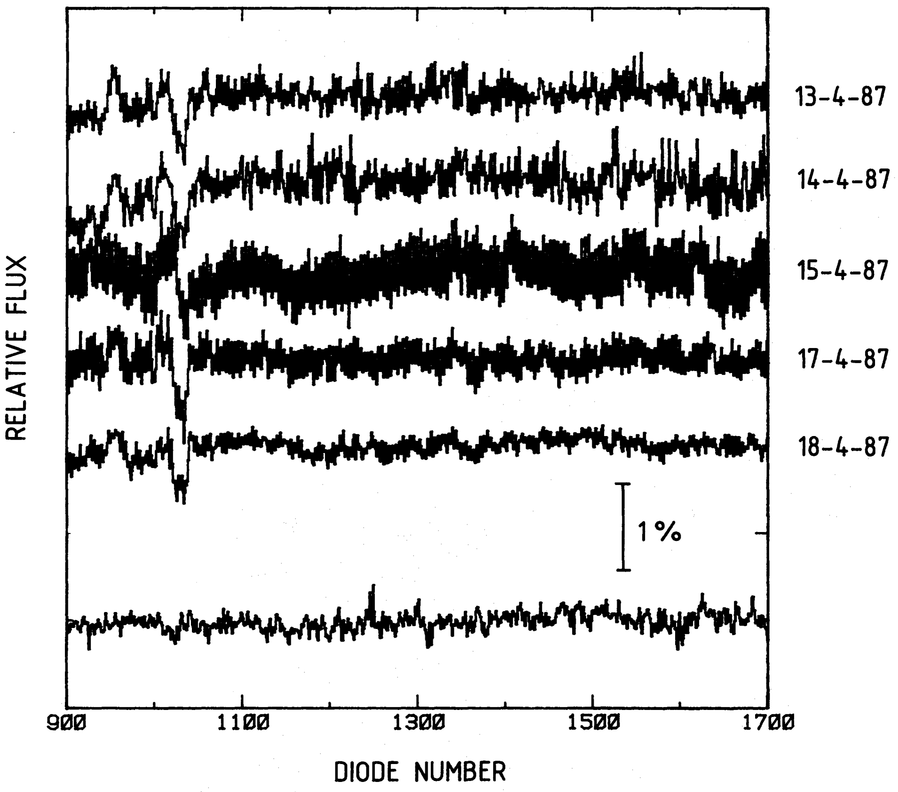

Fig. 2. The spectrum of SN 1987 A around λ 6710 Å as observed with the CES, Long Camera, and Reticon at a resolving power of 80,000. Observing dates are given to the right. The spectrum at the top is the mean of three observations, for all others two integrations have been averaged. Each of the five spectra shown has been obtained at different grating angles. Since for this presentation the data have not been rebinned to constant step in wavelength, the occurence of various weak flat field blemishes is evident. Each Reticon diode is about 1.4 km s^{-1} wide. The bottom profile is the difference between the two observations of April 18. The flux scale in units of the adjacent pseudo continuum is provided by the vertical bar

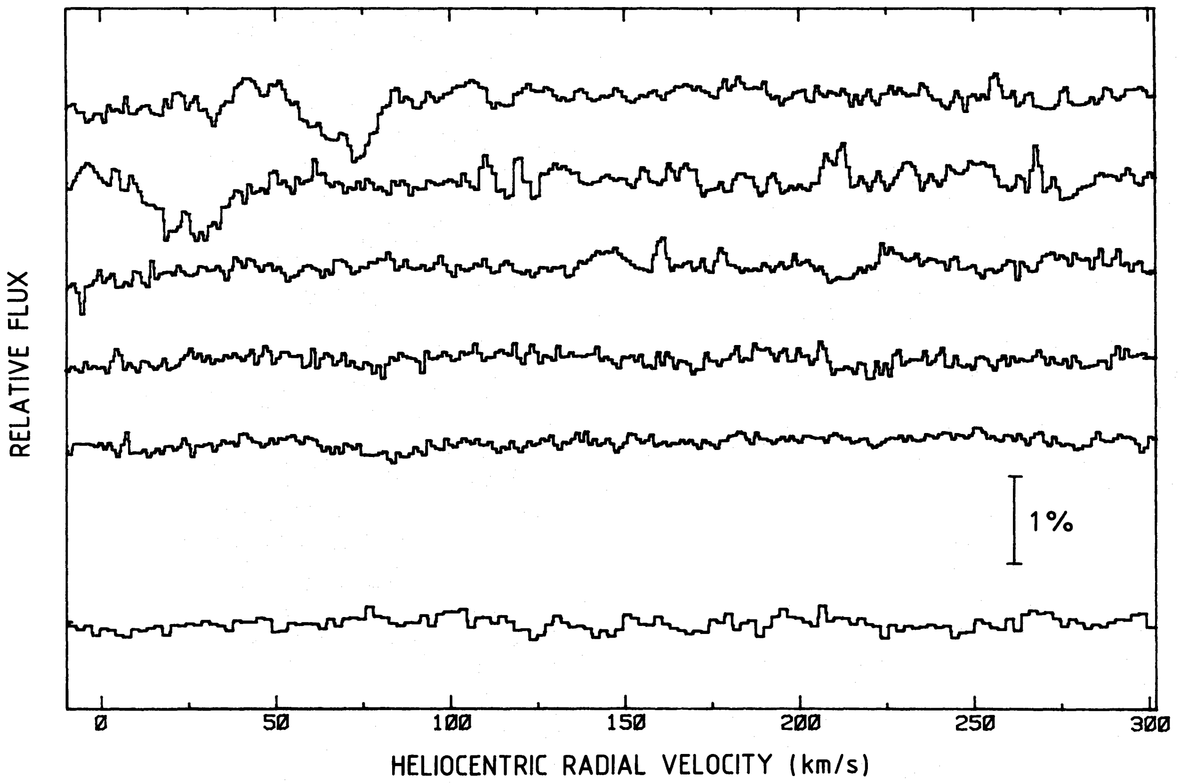

Fig. 3. Same as Fig. 2, but spectra have been rebinned and aligned in heliocentric radial velocity assuming 6707.81 Å for the weighted mean laboratory wavelength of the ^{7}Li doublet. Fourier cleaning for various periodic ripples has in some cases accomplished a significant improvement of the S/N. For the identification of flat field defects compare with Fig. 2 above. The bottom profile is the mean CCD spectrum of Fig. 1. The flux scale is the same as in Fig. 2

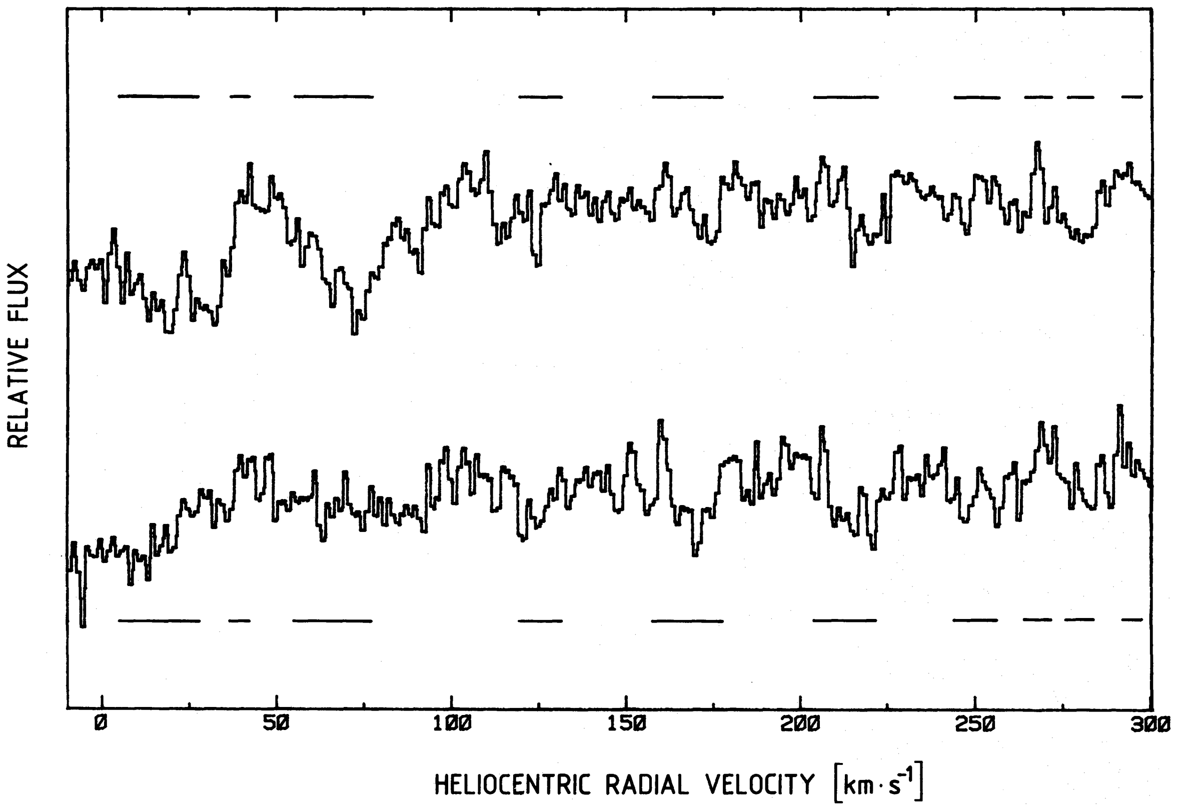

Fig. 4. Weighted averages over all five (upper spectrum) and the last two (lower spectrum) Reticon nights, respectively; in either case all CCD spectra have been included (cf. Fig. 3; see also Sect. 3). The horizontal bars at the bottom and the top of the frame delineate the velocity regions with major Ca II and Na I line complexes (see also Table 1 and text), while the flux scale is the same as in Fig. 1

4. Results and discussion

4.1. Equivalent width limits

For the reasons stated above, we have formed two mean spectra from the data available to us. The first is the mean over all Reticon and CCD spectra, the second one the mean over the CCD spectra and the last two Reticon nights only. In either case the weight assigned to a CCD spectrum has been 0.25; each Reticon spectrum selected has been given unity weight. The results are plotted in Fig. 4. The S/N per diode measured in portions of the spectrum without low-frequency blemishes is 3000 for the first mean and still better than 2100 for the second mean. In spite of the improvement in S/N over the one attained by Vidal-Madjar et al. (1987) we again do not recover the features suggested by Vidal-Madjar et al. to be positive detections.

From the Ca II and Na I data of Andreani et al. (1987), Magain (1987), and Vidal-Madjar et al. (1987) we have selected 6 velocity ranges in which major concentrations of interstellar gas have been detected. In nearly all of them there happen to be quasi-absorption features in our mean spectra. But none is stronger than one would expect from the noise, and the alignment in velocity with weigthed means of the respective Ca II or Na I components is mostly rather unconvincing. We have measured the equivalent widths of these features irrespective of their width, misalignment, etc. The results for the two mean spectra defined above are given in Table 1.

The numbers obtained range from 0.05 to 0.17 mÅ. The largest of them could, in principle, be 1σ detections, but in view of the other mismatches such as in line width and position or between our two mean spectra we consider all results as upper limits at best. In the discussion below we shall only consider the velocity ranges 6–25 km s^{-1} and 270–290 km s^{-1} which comprise the primary Galactic and LMC components, respectively. Rather arbitrarily we adopt 0.15 mÅ as the upper limit for either of them which in our opinion is sufficiently conservative to have no significant effect on the overall error budget of the abundance limits derived below.

Table 1. Upper limits for the equivalent widths of interstellar Li λ 6708 Å lines toward SN 1987 A

Velocity range (km s^{-1})	*EW* in 1. mean [a] (mÅ)	*EW* in 2. mean [b] (mÅ)
6– 25	–	0.14
55– 78	–	0.07
118–132	0.08	0.08
162–177	0.06	0.17
210–225	0.15	0.10
275–290	0.09	0.08

[a] All Reticon (weight 11 × 1.0) and all CCD (weight 7 × 0.25) spectra, cf. text
[b] Reticon spectra (weight 4 × 1.0) of last 2 nights and all CCD spectra (weight 7 × 0.25), cf. text

These upper limits are still clearly lower than the figures (0.2 mÅ for the Galaxy and 0.5 and 0.3 mÅ for the LMC) given by Vidal-Madjar et al. (1987) and proposed to be positive detections. However, the features marked "GAL" and "LMC" in their Fig. 2 are only somewhat broader but not deeper than spikes in the noise. Their coincidence with the expected positions may therefore well be accidental (and, in fact, is rather imperfect since close inspection of Vidal-Madjar et al.'s [1987] Fig. 2 suggests a deviation in wavelength by up to several tenths of an Å).

4.2. Column density limits

Because at high S/N we do not detect the lithium lines searched for, the assumption of optically thin lines makes sense for the conversion of the upper limits from equivalent widths, EW, to column densities, N. Using the relation $N = EW(mc^2/\pi e^2 \lambda^2 f)$ with a weighted-mean oscillator strength $f = 0.75$ (Wiese et al. 1966), we derive $N(\text{Li I}) \leqq 5.0\ 10^8\,\text{cm}^{-2}$ for both the Galaxy and the LMC (because for either we adopt the same upper limit in EW). Note that although in equivalent width our detection limits are below the figures given by Vidal-Majar et al., our upper limits for the column density exceed the suggested detections by Vidal-Madjar et al. (1987) who seem to have used an incorrect factor for the transformation from EW to N.

With ionization potentials of 5.4 eV for Li I and 75.3 for Li II, most of the interstellar lithium is singly ionized, and the elemental column densities will be quite different from the ionic ones given above. Since interstellar Li II lines are not readily accessible, the ionization correction is usually obtained by comparison with the ionization of other elements, e.g. calcium, observed in the same interstellar clouds:

$$N(\text{Li II}) = N(\text{Li I}) \times N(\text{Ca II})/N\,(\text{Ca I}) \times [(\Gamma/\alpha)_{\text{Li}}/(\Gamma/\alpha)_{\text{Ca}}] \qquad (1)$$

The ratio of the photoionization coefficient, Γ, and the recombination coefficient, α, has been modeled by Herbig (1968) for, i.e., both lithium and calcium. We use here the long-distance limit for $[(\Gamma/\alpha)_{\text{Li}}/(\Gamma/\alpha)_{\text{Ca}}]$, namely 1.6.

Column densities for the relevant Ca I and Ca II components along the line of sight to SN 1987 A have been given by Vidal-Madjar et al. (1987) and Magain (1987). In spite of the lower spectral resolution at which they were obtained we choose the ones of Magain because of indications (Magain, 1986, unpublished; Andersen et al., 1987) that EWs measured in CES CCD spectra are systematically higher than in CES Reticon spectra. The reason for this difference is not clear. Scattering in the long camera which is exclusively being used with the Reticon has been named (Andersen et al., 1987), but signal remanence in the Reticon from previous exposures may well also be involved. Although the effect generally is small, it becomes important when the ratio between a strong and a weak line is needed like the one between the strong Ca II and the typically 50 times weaker Ca I lines entering into Eq. (1).

Thus, using $N(\text{Ca II}/N(\text{Ca I})$ ratios of 320 and 175 for the Galaxy and the LMC, respectively, we deduce elemental lithium column densities of $\leqq 2.6\ 10^{11}\,\text{cm}^{-2}$ for the Galaxy and $\leqq 1.4\ 10^{11}\,\text{cm}^{-2}$ for the LMC. Because of the need to infer the population of the primary ionization stage from observations of a minority ion and from the equivalent width ratio of a strong and a very weak line of another element, the errors probably readily exceed a factor of 2.

4.3. Abundance limits

21 cm H I column density measurements with a 15′ beam by Rohlfs et al. (1984) along 14 lines of sight within $\sim 30'$ of SN 1987 A range from 9.7 to $29.6 \times 10^{20}\,\text{cm}^{-2}$ for components with velocities very close to the ones encountered in Na I and Ca II (Vidal-Madjar et al., 1987; Andreani et al; Magain, 1987). Our column density therefore translates into an interstellar gaseous abundance ratio $(\text{Li/H I})_{\text{LMC}} \leqq 0.5 - 1.4\ 10^{-10}$. Since in the map of Rohlfs et al. the H I distribution in the direction of SN 1987 A appears skewed, possibly because of unresolved sources, a value at the upper end of the range in abundances may be preferred.

Another estimate of the H I column density is made possible by the recent $E(B-V)$ vs. H I column density calibration for the LMC by Fitzpatrick (1986) which reveals a higher gas-to-dust ratio than in the Galaxy: $N(\text{H I})/E(B-V) = 2.4\ 10^{22}\,\text{cm}^{-2}\,\text{mag}^{-1}$ with a possible trend toward lower values outside the 30 Dor region. Various authors (West et al., 1987; Danziger et al., 1987; Panagia et al., 1987) have given estimates for the reddening of SN 1987 A between 0.2 and 0.25 mag. Assuming that the typical foreground reddening due to dust in the Galaxy is ≈ 0.07 mag (Brunet, 1975), a value of 0.1 mag for the reddening within the LMC appears reasonably safe. Application of Fitzpatrick's (1986) calibration then yields $N(\text{H I})_{\text{LMC}} = 2.4\ 10^{21}\,\text{cm}^{-2}$ which differs by only a factor of 0.8 to 2.5 from the radio data of Rohlfs et al. (1984) and corresponds to an abundance limit $(\text{Li/H I})_{\text{LMC}} \leqq 0.6\ 10^{-10}$. From these two estimates we take 1.0 10^{-10} as the most probable value and estimate that a factor of 2 is also representative of the error involved when converting our column densities into elemental abundances.

In a similar fashion, namely with $E(B-V)_{\text{Galaxy}} = 0.07$ mag and the mean relation $N(\text{H I})/E(B-V) = 4.8\ 10^{21}\,\text{cm}^{-2}\,\text{mag}^{-1}$ valid for the Galaxy (Bohlin et al., 1978), the galactic Li/H I ratio along the line of sight to SN 1987 A becomes $\leqq 7.7\ 10^{-10}$.

The Galactic upper limit is rather at the lower end of the positive derections reported for other lines of sight (see the compilation by Hobbs, 1985) where relative gaseous abundances $(\text{Li/H I})_{\text{Galaxy}}$ between 0.27 and 110 10^{-10} have been found. The upper limit for the LMC is even lower by almost an order of magnitude and therefore very low indeed. A similarly low abundance Li/H $\approx 1.2\ 10^{-10}$ in Pop. II stars has been reported by Spite and Spite (1982; see also Spite et al. 1984; Hobbs and Duncan 1987; direct comparison of their numbers with ours means that molecular and ionized hydrogen in the LMC interstellar medium are neglected) who therefore suggested that the primordial Li/H abundance ratio is 10^{-10} rather than the customarily assumed "canonical" value of 10^{-9}.

Of the nuclei synthesized in significant quantities during the big bang (D, ^{3}He, ^{4}He and ^{7}Li) the nuclear cross sections and parameters are the least certain for ^{7}Li (see Beaudet and Reeves 1984). The diagnostic power of ^{7}Li abundances alone is, in principle, further reduced because the predicted abundances show a pronounced minimum of Li/H $= 0.8\ 10^{-10}$ at a baryon-to-photon number ratio $\eta = 3\ 10^{-10}$ and a steep rise towards both lower and higher values of η (Yang et al., 1984). Moderate anisotropy changes this dependence only slightly (Kurki-Suonio and Matzner, 1985). On the other hand, a *low* upper limit can, for that matter, restrict the possible range of η quite considerably. If in the interstellar medium of the LMC no substantial net depletion of ^{7}Li has taken place, our value of Li/H I would therefore tend to reinforce the conclusions drawn by Yang et al. (1984) for the baryon-to-photon ratio.

The significance of a single non-detection – even though at a fairly low level – is of course necessarily limited, especially for inferences on a cosmological scale. But it is reminded that with the VLT (a 16 m equivalent telescope) currently being planned by ESO for the 1990's it will be possible to repeat the observations for various lines of sight to the LMC and SMC.

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