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The Lithium Isotope Ratio in Old Stars

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1 Introduction

A number of important observational studies of the light element abundances in old, metal-poor stars have been published in recent years. Beryllium has been detected and found to evolve with a nearly constant ratio to iron (Gilmore et al. 1992, Ryan et al. 1992, Boesgaard & King 1993). Boron has been shown to be about 20 times more abundant than Be, when non-LTE effects in the formation of the B I 2496.7 Å line are taken into account (Duncan et al. 1992, Kiselman 1994, Edvardsson et al. 1994). Thorburn (1994) has made an extensive survey of lithium in very metal-poor, main-sequence stars, which suggests that the abundance of Li increases significantly with increasing metallicity. Finally, ^{6}Li has probably been detected in the metal-poor ([Fe/H] $\simeq -2.4$) turnoff star HD 84937 (Smith et al. 1993, Hobbs & Thorburn 1994) at a level of ^{6}Li/^{7}Li $\simeq$ 0.05. All of these new data are very significant for our understanding of the Galactic evolution of the light element abundances and for the determination of the amount of ^{7}Li produced in the Big Bang phase of the Universe.

In the present paper we concentrate on the lithium isotope problem. The methods and accuracy by which the ^{6}Li/^{7}Li ratio can be determined are discussed. Earlier and recent works on old F and G stars are reviewed and some new observations obtained with the ESO Coudé Echelle Spectrometer (CES) are presented. Finally, the existing results on the lithium isotope ratio and the new data on Be, B and Li abundances are compared with models for cosmic ray production of the light elements as well as the possible depletion of these elements in stellar envelopes.

2 Analysis of the Li I 6707 Å line

The Li I resonance line at 6707 Å is a doublet with hyperfine structure. Accurate interferometric wavelength measurements have been carried out by Meissner et. al. (1948). The doublet splitting is 0.152 Å and the isotope shift is 0.158 Å with ^{6}Li having the longest wavelength (see Table 1 of Andersen et al. 1984). Hence,

the stronger doublet component of ^{6}Li is superimposed on the weaker ^{7}Li component. Due to the various line broadening effects in a stellar atmosphere a skew but rather smooth profile results. Fig. 1 shows a model-atmosphere calculation of the Li line in HD 160617 for three values of ^{6}Li/^{7}Li. As seen, a change of the ^{6}Li abundance has two effects: i) a shift of the center-of-gravity (cog) wavelength of the Li line amounting to 15 mÅ when ^{6}Li/^{7}Li is increased from 0.0 to 0.1, and ii) an increase of the FWHM of the line, which amounts to 18 mÅ for the same increase of ^{6}Li/^{7}Li. Thus, we have essentially two methods to determine the ^{6}Li/^{7}Li ratio: The wavelength method and the profile method.

2.1 The wavelength method

When measuring the cog-wavelength of the Li line we must reduce the observed wavelength for the Doppler shift due to the radial velocity of the star and the gravitational redshift. This Doppler shift can be determined from nearby metallic absorption lines. For the most metal-poor stars ([Fe/H] < -2.0) only two lines are available: an Fe I line at 6677.987 Å and a Ca I line at 6717.677 Å. For stars with [Fe/H] $\simeq -1.0$ Fe I lines at 6703.567, 6705.102 and 6726.667 Å may also be used. In metal-poor stars these lines are practically unblended. Accurate wavelengths ($\pm$2 mÅ) of the Fe I lines lines have recently been measured by Nave et al. (1994). Furthermore, M. Rosberg and S. Johansson, Lund, have kindly measured a similar accurate wavelength of the Ca I line. In principle it should therefore be possible to determine the cog-wavelength of the Li I line to an accuracy of say $\pm$2 mÅ, which would correspond to about $\pm$0.01 in ^{6}Li/^{7}Li. However, as discussed in detail by Nissen et al. (1994a), the Doppler shift determined from lines with high and low excitation potential lines differ by up to 6 mÅ (0.3 km s^{-1}), which translates to an error of 0.04 in ^{6}Li/^{7}Li. These small differences in the Doppler shift are probably caused by convective motions in the stellar atmosphere. Similar systematic differences are seen in the solar spectrum (Dravins et al. 1981), and have been explained by a hydrodynamical model in which hot, rising bright granules are balanced by a downflow in darker (cooler) inter-granular regions. The result is a convective blueshift of the lines, which is more pronounced for the weak high excitation lines because they are formed deep in the atmosphere where the convective motions are more vigorous.

We conclude that until the convective blueshift of lines in the spectra of metal-poor stars have been mapped as a function of line strength and excitation potential we cannot use the cog-wavelength of the Li I resonance line to determine very accurate values of the lithium isotope ratio. For the time being the profile method appears more accurate.

2.2 The profile method

In this method the observed profile of the Li I line is compared with synthetic, model-atmosphere spectra computed for various values of ^{6}Li/^{7}Li (see Fig. 1). The basic problem is that the broadening of the Li I line due to stellar rotation and macro-turbulent motions in the atmosphere must be determined from

other lines in the spectrum. As an example we briefly discuss HD 160617, that was recently observed with the ESO CES (Nissen et al. 1994a) in the spectral region 6676 - 6734 Å with a resolution of R = 115.000 and a S/N = 400. Synthetic spectra were computed by the aid of a programme *BSYN* kindly made available by the stellar atmosphere group in Uppsala. The model atmosphere used has parameters, $T_{\rm eff}$ = 5800 K, log$g$ = 3.8 and [Fe/H] = −2.0 . The model atmosphere computation includes thermal and microturbulent broadening with ξ_{turb} = 1.7 km s^{-1} as determined by Nissen et al. (1994b). In order to determine the broadening due to the combined effects of the instrumental profile and stellar rotation and macro-turbulence the synthetic spectrum was convolved by various broadening functions and compared to the observed profile of the Fe I line at 6678 Å. It turns out that pure rotational broadening does not lead to a satisfactory agreement between the observed and the synthetic profile. The best fit is obtained with a so-called radial-tangential profile (Gray 1976), which corresponds to radial and tangential motions in the atmosphere each with a Gaussian distribution of the velocities. The radial-tangential profile is more V-shaped than the U-shaped profiles corresponding to pure rotation or isotropic Gaussian broadening.

Fig. 2 shows the resulting fit of the Fe I line for three values of the velocity broadening parameter ζ_{RT} = 4.3, 5.0 and 5.7 km s^{-1}. The equivalent width is the same for the observed and the synthetic lines. From the comparison we determine ζ_{RT} = 5.0±0.3 km s^{-1}. Very nearly the same value is determined from the Ca I line at 6717 Å. The fit is, however, not perfect. A slight asymmetry is seen in the wings of the Fe I line - probably caused by the convective motions in the stellar atmosphere.

In Fig. 1 the observed profile of the Li I line of HD 160617 is compared to three synthetic profiles corresponding to ^{6}Li/^{7}Li = 0.0, 0.1 and 0.2, respectively, all folded with a radial-tangential broadening function having ζ_{RT} = 5.0 km s^{-1} as determined from the analysis of the Fe I line. As seen, the profile corresponding to ^{6}Li/^{7}Li= 0.0 gives a nearly perfect fit to the data. Hence, there is no evidence of the presence of ^{6}Li in HD 160617. From Fig. 1 an upper limit ^{6}Li/^{7}Li < 0.02 can be set.

3 Determinations of the Li isotope ratio

3.1 Previous attempts

Herbig (1964) and Feast (1966 and 1970) were apparently the first to study the lithium isotope ratio in bright solar-type stars. High-dispersion, photographic spectra were analyzed with the wavelength method. Feast concluded that the results were consistent with an upper limit of about 0.5 for the ^{6}Li/^{7}Li ratio, and that this high value was in fact reached in subgiants. Cohen (1972), however, showed that the upper limit of ^{6}Li/^{7}Li was 0.1 in 14 bright F, G and K stars, which she observed with a Fabry-Perot scanner at a resolution of 70.000 and a S/N of about 50.

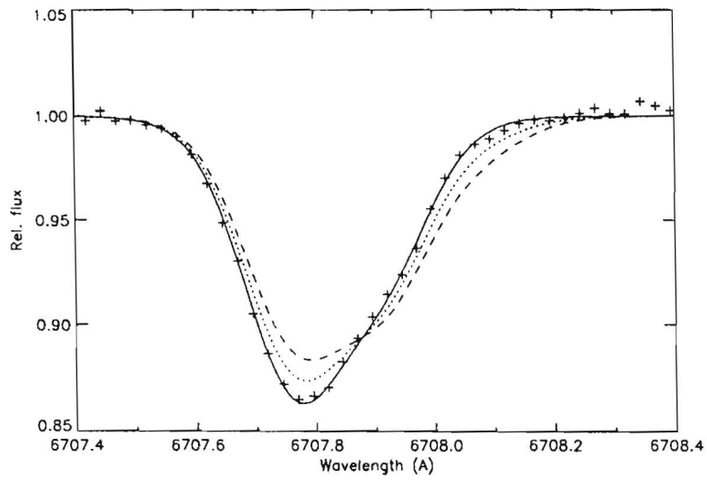

Fig. 1. The observed profile (+) of the Li I line of HD 160617 compared with synthetic model-atmosphere profiles convolved with a radial-tangential broadening function with $\zeta_{RT} = 5.0$ km s^{-1}and corresponding to ^{6}Li/^{7}Li = 0.0, 0.1 and 0.2, respectively

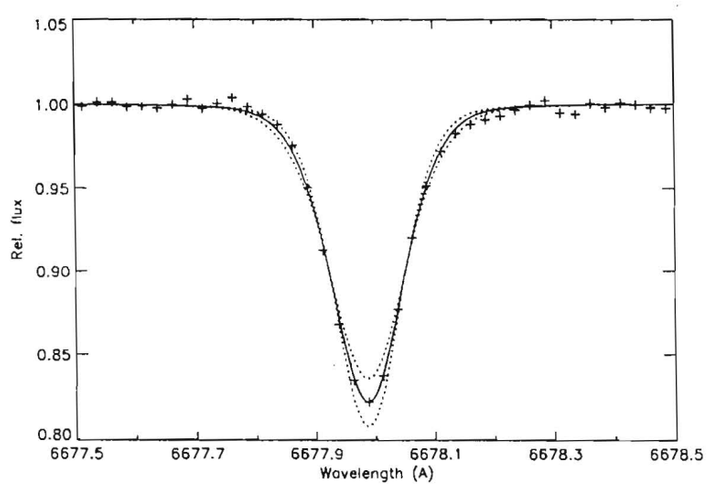

Fig. 2. The observed profile (+) of the Fe I line of HD 160617 compared with a synthetic model-atmosphere profile convolved with a radial-tangential broadening function with $\zeta_{RT} = 4.3$, 5.0 and 5.7 km s^{-1}, respectively

Following the construction of new effective, high resolution echelle spectrometers equipped with sensitive, linear detectors a number of important studies of the $^6Li/^7Li$ ratio appeared. Andersen et al. (1984) used the ESO CES to set an upper limit of $^6Li/^7Li < 0.1$ for 8 solar-type dwarfs. Maurice et al. (1984) used the same spectrometer to study four metal-deficient stars. The upper limit for two old disk stars were $^6Li/^7Li < 0.05$, whereas the limit for two halo stars (ν Ind and HD 76932) were $^6Li/^7Li < 0.1$. Hobbs (1985) using the coudé spectrograph of the 2.7 m telescope at the McDonald Observatory also found an upper limit $^6Li/^7Li < 0.1$ in a study of 5 F and G dwarfs. Finally, Pilachowski et al. (1989) made a careful analysis of the metal-poor, turnoff star HD 84937 and derived the limit $^6Li/^7Li < 0.1$. All of these results were based on the profile method.

3.2 Recent studies of HD 19445 and HD 84937

The studies just mentioned were based on spectra of the Li I line having a resolution of about 100,000 and a S/N of 100 to 200, except in the case of Maurice et al. (1984), who used spectra with S/N $\simeq$ 300 but a resolution of about 50,000 only. In an attempt to reach a higher accuracy in the determination of the lithium isotope ratio Smith, Lambert & Nissen (1993) (hereafter SLN) used the McDonald Observatory's 2.7 m reflector and coudé spectrometer to obtain spectra with S/N $\simeq$ 400 and $R = 125,000$ for two stars, HD 19445 and HD 84937. The atmospheric parameters are ($T_{\rm eff}$, log$g$, [Fe/H]) = (5820, 4.6, −2.2) for HD 19445 and (6090, 4.0, −2.4) for HD 84937 according to SLN. Hence, as discussed by SLN, HD 19445 is a main-sequence star with a mass of about 0.7 $M_\odot$, for which one expects nearly complete depletion of ^{6}Li, whereas most of the ^{6}Li has survived in HD 84937 according to standard stellar models.

SLN derived the $^6Li/^7Li$ ratio in the two stars by the profile method. The velocity broadening was determined from the Ca I 6162 Å line. In Fig. 3 the fit to the Li I line is shown for the two stars. The total abundance of Li was chosen so that the equivalent widths of the synthetic and the observed lines are equal, and the Doppler shift was set to get the best overall fit. Using the sum of (observed − synthesis) residuals across the Li I line SLN got the following results:

$$\text{HD 19445: } ^6Li/^7Li = 0.00 \pm 0.02$$

$$\text{HD 84937: } ^6Li/^7Li = 0.05 \pm 0.02$$

The main contribution to the quoted (one sigma) error arises from the noise in the observed spectrum and the error in the determination of the velocity broadening parameter ($\pm 0.4\,\mathrm{km\,s^{-1}}$). As discussed by SLN errors in the model atmosphere parameters and the microturbulence do not affect the derived Li isotope ratio significantly. The same conclusion was reached by Andersen et al. (1984) and Maurice et al. (1984).

Recently, Hobbs & Thorburn (1994) have studied the lithium isotope ratio in six halo stars including HD 19445 and HD 84937. New observations were obtained with the same equipment as used by SLN. This independent study by Hobbs & Thorburn resulted in $^6Li/^7Li \leq 0.04$ for HD 19445 and $^6Li/^7Li = 0.07 \pm 0.03$ for

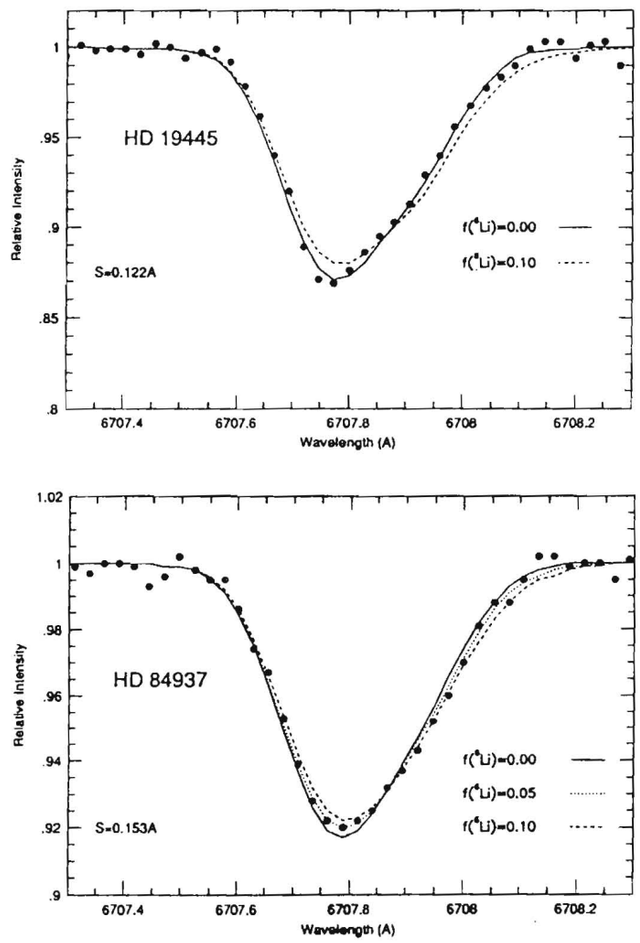

Fig. 3. The observed profiles (•) of the Li I line of HD 19445 and HD 84937 compared with synthetic model atmosphere profiles for various ^{6}Li/^{7}Li ratios. S is the FWHM of the Gaussian smoothing function as determined from the observed profile of the Ca I 6162 Å line. See Smith, Lambert & Nissen (1993) for details

HD 84937. When combined with SLN the detection of ^{6}Li for HD 84937 seems highly significant from a statistical point of view. The most critical assumption is that the velocity broadening profile determined from the Ca I line at 6162 Å is also valid for the Li I line. The Ca I line is slightly stronger and has a higher excitation potential than the Li I line. Hence, the depth of formation in the atmosphere is not exactly the same for the two lines. Clearly, this problem should be further studied by determining the velocity broadening profile for many lines

with different strength and excitation potential.

The best argument for the reality of the detection of ^{6}Li in HD 84937 is that a difference $\Delta(^6\mathrm{Li}/^7\mathrm{Li}) = 0.05 \pm 0.02$ relative to HD 19445 is found. The two stars were observed and analyzed in exactly the same way and they have similar model atmosphere parameters. One would therefore expect that a possible systematic error in the derived ^{6}Li/^{7}Li would be the same for the two stars. HD 19445 so to say sets the zero point of the method.

4 Discussion and conclusions

As discussed in detail by Steigman et al. (1993) the presence of ^{6}Li in the atmosphere of HD 84937 at a level of 5% of the ^{7}Li abundance is consistent with the measured Be abundance (Boesgaard & King 1993) in this star within the context of i) Standard Big Bang nucleosynthesis, ii) Pop. II cosmic ray nucleosynthesis and iii) standard (non-rotating) models for Li depletion. In particular, Steigman et al. derive $D_6 > 0.2$, where D_6 is the depletion factor for ^{6}Li. As shown by Chaboyer (1994) standard stellar evolution models with new opacities predict $D_6 \simeq 0.4$ for turnoff stars and subgiants with $T_{\mathrm{eff}} > 5900\,\mathrm{K}$, whereas $D_6 < 0.01$ for a main-sequence star like HD 19445 with $T_{\mathrm{eff}} \simeq 5800\,\mathrm{K}$. The same models predict $D_7 \simeq 1.0$, i.e. no ^{7}Li depletion for both main sequence and subgiants with $T_{\mathrm{eff}} \geq 5800\,\mathrm{K}$.

Non-standard models with rotational induced mixing predicting a strong ^{7}Li depletion ($D_7 \simeq 0.1$) (Pinsonneault et al. 1992) seem to be excluded by the detection of ^{6}Li in HD 84937, because the same models predict a very severe ^{6}Li depletion ($D_6 < 0.01$).

It remains to be seen if models predicting a mild ^{7}Li depletion ($D_7 \simeq 0.5$), e.g. the diffusion models of Chaboyer & Demarque (1994), are consistent with the presence of ^{6}Li in HD 84937, but in any case we conclude that the degree of ^{7}Li depletion in Pop. II stars is severely constrained by the amount of ^{6}Li detected in their atmospheres. This has important implications for Big Bang nucleosynthesis; e.g. inhomogeneous Big Bang models predicting $\log\varepsilon(\mathrm{Li}) \simeq 3.0$ can probably be excluded.

In addition to HD 19445 and HD 84937, Hobbs & Thorburn (1994) studied four other Pop. II stars. For two of them an upper limit ^{6}Li/^{7}Li < 0.1 could be set. For HD 140283, a subgiant with $T_{\mathrm{eff}} = 5750\,\mathrm{K}$ and [Fe/H] $= -2.5$, the limit is ^{6}Li/^{7}Li ≤ 0.03. For the fourth star, HD 201891, a detection (^{6}Li/^{7}Li $= 0.05 \pm 0.02$) is claimed. According to Hobbs and Thorburn this star is a subgiant with $T_{\mathrm{eff}} = 5900\,\mathrm{K}$ and [Fe/H] $= -1.5$. It is, however, puzzling that ^{7}Li in HD 201891 ($\log\varepsilon(\mathrm{Li}) = 1.90$) appears to be depleted relative to the plateau value ($\log\varepsilon(\mathrm{Li}) \simeq 2.2$). One would therefore expect ^{6}Li to be totally depleted. We also note that Edvardsson et al. (1993) find HD 201891 to be a main-sequence star with [Fe/H] $= -1.1$ for which one would expect a high degree of ^{6}Li depletion.

Smith, Lambert & Nissen have continued observations of the Li I line with the ESO CES and the McDonald spectrometer. An example of the spectra obtained was discussed in Sect. 2. Preliminary results indicate that the abundance of ^{6}Li

in subgiants with $T_{\rm eff} < 5900$ is less than in the turnoff star HD 84937. This agrees with the limit ^{6}Li/^{7}Li ≤ 0.03 for HD 140283 found by Hobbs & Thorburn (1994). A rapid decline of ^{6}Li for $T_{\rm eff} < 5900$ K due to dilution in connection with the deepening of the convection zone as a star evolves along the subgiant branch is in fact predicted by the standard models of Chaboyer (1994).

In connection with the discussion of depletion coefficients predicted from stellar evolution models it is important to know if the stars observed are subgiants or main sequence stars. According to their positions in the Strömgren $(b-y)-c_1$ diagram (Schuster & Nissen, 1989), HD 140283 and HD 160617 are subgiants and HD 84937 is very close to the turnoff point. As discussed by Chaboyer (1994), the parallax of HD 84937 places the star on the main sequence. However, the parallax is uncertain and the case of HD 140283 shows that parallaxes are sometimes affected by large systematic errors (see discussion by Nissen et al. 1994b). Clearly, accurate HIPPARCOS parallaxes will be very valuable for the discussion of the evolutionary status of the stars for which ^{6}Li has been studied.

We conclude that further studies of the ^{6}Li abundances in metal-poor Pop. II stars are much needed to confirm that turnoff stars and the hottest subgiants do indeed have a small amount of ^{6}Li in their atmospheres. Determinations of ^{6}Li/^{7}Li in somewhat more metal-rich Pop. II stars would also be very interesting. As discussed by Thorburn (1994), one would expect that ^{6}Li/^{7}Li increases with increasing metallicity. Pop. II turnoff stars are however rare. Only one (HD 84937) is brighter than $m_V = 9$. In order to reach the fainter turnoff stars with $R > 100,000$ and S/N > 400 very large telescopes equipped with high quality spectrometers are needed.

References

Andersen, J., Gustafsson, B., Lambert, D.L. 1984, A&A 136, 65
Boesgaard, A.M., King, J.R. 1993, AJ 106, 2309
Chaboyer, B.C. 1994, ApJ Letters (submitted)
Chaboyer, B.C., Demarque, P. 1994, ApJ (in press)
Cohen, J.G. 1972, ApJ 171, 71
Dravins, D., Lindegren, L., Nordlund, Å. 1981, A&A 96, 345
Duncan, D.K., Lambert, D.L., Lemke, M. 1992, ApJ 401, 584
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D.L., Nissen, P.E., Tomkin, J. 1993, A&A 275, 101
Edvardsson, B., Gustafsson, B., Johansson, S.G., Kiselman, D., Lambert, D.L., Nissen, P.E., Gilmore, G. 1994, A&A (in press)
Feast, M.W. 1966, MNRAS 134, 321
Feast, M.W. 1970, MNRAS 148, 489
Gilmore, G., Gustafsson, B., Edvardsson, B., Nissen, P.E. 1992, Nature 357, 379
Gray, D.F. 1976, "The Observation and Analysis of Stellar Photospheres", John Wiley and Sons, p. 426
Herbig, G.H. 1964, ApJ 140, 702
Hobbs, L.M. 1985, ApJ 290, 284
Hobbs, L.M., Thorburn, J.A. 1994, ApJ 428, L25
Kiselman, D. 1994, A&A 286, 169

Maurice, E., Spite, F., Spite, M. 1984, A&A 132, 278
Meissner, K.W., Mundie, L.G., Stelson, P.H. 1948, Phys. Rev. 74, 932
Nave, G., Johansson, S., Learner, R.C.M., Thorne, A.P., Brault, J.W. 1994, ApJS (in press)
Nissen, P.E., Lambert, D.L., Smith, V.V. 1994a, The ESO Messenger 76, 36
Nissen, P.E., Gustafsson, B., Edvardsson, B., Gilmore, G. 1994b, A&A 285, 440
Pilachowski, C.A., Hobbs, L.M., De Young, D.S. 1989, ApJ 345, L39
Pinsonneault, M.H., Deliyannis, C.P., Demarque, P. 1992, ApJS 78, 179
Ryan, S., Norris, J., Bessell, M.S., Deliyannis, C.P. 1992, ApJ 388, 184
Schuster, W.J., Nissen, P.E. 1989, A&A 222, 69
Smith, V.V., Lambert, D.L., Nissen, P.E. 1993, ApJ 408, 262 (SLN)
Steigman, G., Fields, B.D., Olive, K.A., Schramm, D.N, Walker, T.P. 1993, ApJ 415, L35
Thorburn, J.A. 1994, ApJ 421, 318

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