ISAS - INTERNATIONAL SCHOOL
FOR ADVANCED STUDIES

Thesis for the attainment of the title
"Doctor Philosophiae"

DETERMINATION OF THE ABUNDANCES OF LITHIUM, BERYLLIUM AND BORON IN THE POPULATION II STARS AND IN THE INTERSTELLAR SPACE OF THE LARGE MAGELLANIC CLOUD

Candidate: Paolo MOLARO

Supervisor: Prof. Dennis SCIAMA

1987

TRIESTE

SISSA - SCUOLA INTERNAZIONALE SUPERIORE STUDI AVANZATI
TRIESTE
Strada Costiera 11

DETERMINATION OF THE ABUNDANCES OF LITHIUM, BERYLLIUM AND BORON

IN THE POPULATION II STARS

AND IN THE INTERSTELLAR SPACE OF THE LARGE MAGELLANIC CLOUD

Paolo Molaro

INDEX

INTRODUCTION

The astronomical relevance of the observations of lithium in the atmospheres of old stars began in the 1982 when Francoise and Monique Spite, of the Meudon Observatory, using the 3.6m FHCT telescope at Mauna Kea, made the unexpected discovery that lithium whas present in the Population II stars even though amounting to only 10% of the "cosmic" value of $1x10^{-9}$.

At that time it was generally believed on the bases of the assumed age-lithium relation that lithium should have been destroyed in objects older than the sun, where only traces of ^{7}Li can be found. A second, and even greater surprise, was to find that ^{7}Li in Population II stars was nearly constant in all the stars studied. This uniformity lead the Spites to argue that the ^{7}Li observed in Population II objects is precisely the lithium synthesized in the primordial nucleosynthesis. This statement had important implications on the stellar structure theory, on the galactic chemical evolution theory and cosmology, most of which are stil a matter of debate and that we will discuss here in some detail.

After Dennis Sciama drew my attention on the Spites' work, I undertook some research with the aim to extend the measure of ^{7}Li to other population II stars to confirm that ^{7}Li is constant or possibly to find some correlations with stellar properties. The results of this investigation, made in collaboration with J.E. Beckman and R. Rebolo of the Instituto de Astrofisica de Canarias, is given in chapter II, following an introductory chapter on the last views on the origin of the light elements.

We know that in the sun lithium is depleted by two orders of magnitude but beryllium and boron are at the "normal" levels suggesting that these last two elements should survive in the surface material of solar-type stars. Thus the unexpected survival of lithium in the atmosphere of old stars raised the hope to find also the other two related light elements, beryllium and boron, enshrined in the atmospheres of these ancient stars. The firsts efforts to assess the quantity of beryllium and boron in the Population II objects are illustrated in chapters 3 and 4, respectively.

In the last chapter I report the results of a search for interstellar lines of lithium, beryllium and boron in the Large Magellanic Cloud using spectra of the supernova Shelton, that exploded on the 24th February of this year.

1. ORIGIN OF LITHIUM, BERYLLIUM AND BORON

Most of the elements that exist in nature are believed to have been forged by thermonuclear reactions in the stellar interiors (Burbidge, Burbidge, Fowler and Hoyle 1957). As successful as the theory is, it cannot however explain the existence of deuterium, lithium, beryllium and boron, that are by-passed by the chain of nuclear reactions. They are characterized by a fairly weak stability of the nucleus and cannot survive in environements with temperatures higher than a few million degrees, i.e. inside any star ($T=2x10^6$ K for ^7Li, $T=4x10^6$ K for Be and $T=5x10^6$ K for B). For example, ^7Li is formed during the proton-proton chain by $^3He(He,\gamma)^7Be(e^-,\nu)^7Li$. at temperatures of $2x10^7$ K, but it will be destroyed by $^7(p,^4He)^4He$ at a temperature of about $2x10^6$ K. Thus the stellar volume in which light elements are destroyed is much larger than the central region where they may be created and the stars are in fact lithium destroyers. The same occurs for the other light elements, yet they exist in nature.

Burbidge , Burbidge, Fowler and Hoyle (1957) pointed out that these elements could be synthesized only in a low-density and cold medium to prevent their fragmentation after the formation (the so called "X" process). The first hypothesis has been the "autogenetic" theory, where spallation processes occuring in the active stellar surfaces of young objects were supposed to produce all the light elements in nature. This has subsequently been proven to be unlikely for the large scale homogeneity detected in observations and bacause it has been proven that a star to produce these elements at the a cosmic value requires an amount of energy comparable to its total gravitational energy (Ryter et al 1970). The failure of this theory lead Reeves, Fowler and Hoyle (1970) to suggest that the production of these elements could be ascribed to the galactic cosmic rays impinging on the interstellar medium. Simultaneously the detailed calculation of the primordial cosmological nucleosynthesis done by Wagoner, Fowler and Hoyle 1970 showed that ^{7}Li could be synthesized in the first minutes of the universe. The nucleosynthesis process induced by cosmic rays is the only viable way to produce the beryllium and boron observed in nature.

Most of the interest of astrophysicists in observing lithium, beryllium and boron derives from the fact that these elements are destroyed in the inner part of the stars and occupy a special place in the nucleosynthesis scheme. Observations of these light elements in stellar atmospheres are useful to probe the internal structure, and from the evolutionary abundance curve it is possible to infer information on the behaviour of galactic cosmic rays and on the chemical evolution in the Galaxy from the time of its origin.

1.1 COSMOLOGICAL LITHIUM NUCLEOSYNTHESIS

The first primordial nucleosynthesis computation, taking into account helium only, was carried out by Peebles 1966.

Simultaneously Wagoner, Fowler and Hoyle (1967) considering all the relevant nuclear reactions, showed that in the conditions required to synthesize ^4He and D at the observed levels appreciable quantities of ^7Li were produced.

At that time the result was not considered particularly relevant because the estimated value of $^7Li/H$ was about $4x10^{-11}$ while the observed lithium was about $1x10^{-9}$. During the big bang, for low values of the baryon-to-photon number ($\eta<3x10^{-10}$), the mass 7 is produced through the $^3H(He,\gamma)^7Li$ reaction and destroyed through the $^7Li(p,\alpha)^4He$ reaction. For higher values of this ratio the reaction $^3He(He,\gamma)^7Be$ is dominating and the destruction occurs through the $^7Be(n,a)^4He$ reaction mainly because the high coulomb barrier inhibits charged reactions. It is clear that the final product is particularly sensitive to the cross sections of these reactions.

A subsequent revision of the relevant cross section has slightly changed the primordial yields in the last two decades (Wagoner 1969 and 1973, Yang et al 1979, Olive et al. 1981). In particular ^7Li was affected by the new cross reactions provided by Fowler Caughlan and Zimmerman 1975, and in Olive et al 1981 the ^7Li output was a factor 3 times higher than the original computations of Wagoner (1973). Nuclear uncertainties of the big bang yields have been treated in some detail in Beaudet and Reeves (1984), and lithium estimate is thought to be accurate within a factor two.

In the early 80's the Spite and Spite's discovery of ^7Li in Population II stars implied a lowering of the observational limit of the primordial lithium converging towards the theoretical estimates. The comparison between observations and theory is discussed in some detail in Yang et al (1984), and Boesgaard and Steigman (1986).

Very recently two groups, Kawano, Schramm and Steigman 1987 and Kajino Toki and Austin 1987 have independently reconsidered the ^7Li primordial production introducing new values for some cross sections.

Kawano et al (1987) used the new cross section by Schroder et al. (1986) who have found a twofold increase in the cross section at zero energy (S(0)) for the reaction $^3H(^4He,\gamma)^7Li$. For the reaction $^7Li(p,^4He)^4He$ they used the cross section at zero energy developed by Rolf and Kavanaugh (1986), 52 ± 8 Kev-barns compared to 65 Kev-barns in previous studies. However this new reduction does not, in itself, change the yield significantly. Using this new reaction rates they revaluate the primordial production of lithium by a factor of 1.5 for low values of baryon-to photon number. The results are shown in Figure 1.1.

Kajino et al. 1987 observed that theoretical calculations based on the "resonanting group calculation", which accounts for the alpha-particle like correlation, give more reliable description of the observational data. Thus they applied the same theoretical results to fit the experimental data in order to extrapolate the S-factor of the $(^4He,\gamma)$ reactions to low energies. We note that Kawano et al (1987) reached the same conclusion and in this respect the two computations are similar. For the other reactions they used the cross sections of Cauglan et al (1985). For the $^7Li(p,^4He)^4He$ reaction which destroies ^7Li after its formation, they used the S factor obtained by Barker (1972). This value is close to that of Fowler et al (1975), used in Yang et al (1984). They found that the the big bang products are much more similar to calculations based on Fowler et al (1975) rates, like those of Yang et al 1984, the typical difference being 20 % or less.

The most relevant difference pointed out by Kajino et al (1987) as against the previous computations is a degree of uncertainty much lower than the factor 2 considered by Yang et al (1984). They noted that the reaction rates for the $^{7}Li(p,\alpha)^{4}He$, $^{3}H(\alpha,\gamma)^{7}Li$ and $^{3}He(\alpha,\gamma)^{7}Be$ are known at about 15%, 25% and 6%, respectively. Globally the reaction rates are sufficently accurate and the uncertainty in the big bang production of ^{7}Li is $\pm$35% at all the relevant densities (<20% for high values of baryon-to-photon number).
Their results are reported in Fig 1.2

The significant fact introduced by the computations of Kajino et al (1987) is that now, for the first time, the amount of ^{7}Li estimated in the big bang for a given baryon density is more accurate than observational measurements.

It must be said, however, that the standard model rests on some foundamental assumptions, and the above mentioned results for lithium are reached only if the same assumptions are adopted. Several studies have been carried out on deviations from the standard model and we shall not enter into details here. We shall just stress that lithium, in most cases, place stringent constraints on the departures from the canonical big bang.

1.2. SPALLATION PRODUCTION OF BERYLLIUM AND BORON (AND LITHIUM)

The origin of beryllium and boron was an astrophysical puzzle until the '70s when Reeves, Fowler and Hoyle (1970) suggested that they - together with some Li - could be the product of spallation processes between energetic galactic cosmic rays and interstellar gas.

The spallation reaction consists in the partial destruction of a complex nucleus induced by the collision with an energetic light nucleus such H or He. Several reviews have been already devoted to this problem (Audouze and Reeves 1982 and Audouze 1986).

The physical characteristics of the spallation reactions are now very well established in the frame of the classical two step model of Serber 1947: a rapid (10^{-22} sec) first step during which the incoming particle crosses the target nucleus and collides a few nucleons. During a second, much longer (10^{-16} sec), step, called nuclear evaporation, the excited nucleus evaporates a few more nucleons.

The cross sections are accurately known now, including those of the crucial $^{4}He+^{4}He$ reactions leading to ^{6}Li, ^{7}Li and ^{7}Be. The destruction cross-section for the ^{12}C and ^{16}O with energetic protons, for which good experimental data are available, are shown in Figs. 1.3 and 1.4.

Spallation reactions are endothermic and energies greater than a few Mevs are required to induce the reaction, the exact threshold energy depending on the specific reaction. For energies greater than 100 Mev the cross-sections remain nearly constant. The probability of having one product is related to its mass. Mass 11, followed by masses 10,7,6 and finally by mass 9 give the highest probability. It is particularly significant that this order is the same as that of the fluxes observed in the galactic cosmic rays and, with the exception of ^7Li, of the cosmic abundances.

The main characteristics of the cosmic rays are presented in Figs 1.5 and 1.6. It is possible to see that most of the particles have energies around 1 GeV and it has been suggested that most of lithium beryllium and boron is formed by spallation reactions with galactic cosmic rays of these energies. Below 500 MeV the fluxes of galactic cosmic rays are contaminated by solar modulation and are poorly known. This fact introduces a considerable uncertainty in the detailed computation of the yelds of the spallation processes.

At higher energies the galactic cosmic ray flux is $E^{-2.6}$, where E is the total energy (rest mass +kinetic energy).

In the cosmic rays the amounts of lithium beryllium and boron are comparable with those of CNO particles, unlike in the cosmic amounts pointing out once again the effective occurrence of these processes.

The light elements we observe today come from two slightly different mechanisms:

1) the energetic H and ^4He bombarding the interstellar heavy nuclei produce light elements with energies nearly at rest

2) The CNO nuclei forming the GCR collide with interstellar H and He nuclei producing energetic lithium, beryllium and boron than later slow down and mix with the interstellar medium.

Detailed computation of the processes have been done by

Meneguzzi et al 1971. They found that the most important targets are the nuclei of C, N, and O, and that heavier targets are less important because rarer. ^4He particles, that are about 10% of the protons, are also important but they do not make a major contribution.

Meneguzzi et al 1971 estimated that, taking the present observed flux of galactic cosmic rays, about 70% of the products come from the mechanism 1) and 30% from mechanism 2).

The simplest version of the model assumes that the composition and energy spectrum of the cosmic rays have remained constant over the 10-15 billion-year history of the Galaxy. The success of this model is immediately evident considering that the integration of the present production rate for ^9Be, $^{10,11}B$ and ^6Li over a time interval of 10^{10} years gives aproximately the observed amounts. On the other hand ^7Li is underproduced by one order of magnitude and the boron isotopic ratio does not fit properly. ($^{11}B/^{10}B$ comes out about 2 instead of 4.05 ± 0.05 observed in meteorites).

As suggested by Meneguzzi et al (1971), the low-energy cosmic rays, which cannot be observed, could be responsible for the formation of the missing ^7Li and ^{11}B this because there are reactions as $^{14}N(p,\alpha)^{11}C(e^+)^{11}B$ and $^4He+^4He$ with thresholds below 10 MeV.

The effects of the galactic evolution on the formation of the light elements has been investigated by many authors (Truran and Cameron (1971), Mitler (1972), Meneguzzi et al (1971), Audouze and Tinsley (1974), Reeves and Meyer (1978)). The supernova rate related to the cosmic rays flux, the metal content of the interstellar gas, the extent of the processing of matter through stars (astration) and the possible presence of infall of intergalactic gas are of particular relevance to the production and destruction of the light elements are. If the cosmic rays are originated in supernovae or pulsars they are proportional to the death rate of the appropriate stars, and that the cosmic-ray intensity might have been greater in the past.

To illustrate in general terms the effects of these parameters on the amounts of light elements Audouze and Tinsley (1974) have considered two models of galactic evolution, internally consistent but with marked differences. We do not intend to enter into the details of these models but it is important to note that they have shown that under particular circumstancies the light elements can be synthesized quite rapidly. In particular ^7Li can be syntesized very early even before the formation of the Population II stars. Thus enhanced spallation can be considered a possible alternative to the suggested primordial origin for the lithium observed in population II stars.

1.3. Alternative production of lithium

The origin of Li is rather puzzling since it can be produced in several environments.

Large Li amounts are observed in the envelopes of some red giants. Such a presence can be explained by the Cameron and Fowler (1971) mechanism, but since the real fraction of lithium-rich red giants is unknown it is not clear wether this mechanism is at all responsible for some of the lithium observed on a galactic scale. Another plausible mechanism is a possible lithium synthesis during nova explosions (Starrfield et al 1978). The effects of this lithium production have been investigated by Audouze et al (1983) and by Abia and Canal (1987), that showed that they can be the resposible for a lithium enhancement during the galactic life.

Other proposed mechanisms concern cosmological cosmic rays (Montmerle 1977) and supernovae postshock nucleosynthesis (Arnauld and Norgaard 1975). However in these models the isotopic ratios and the other light elements raise problems. Finally thermonuclear production of lithium in supermassive stars (Norgaard and Fricke 1976) has been suggested as a more exotic mechanism.

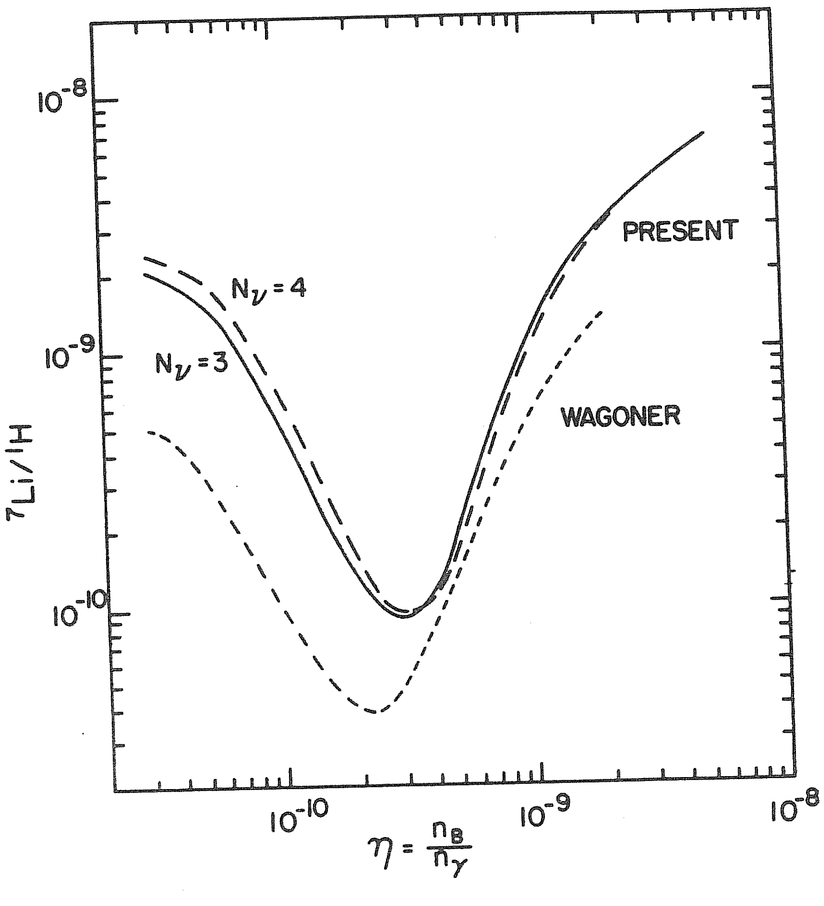


Fig 1.1 From Kajino et al 1987. Primordial abundance of ^7Li produced in a standard big bang expansion. Solid (dashed) curve is the result for N=3 (N=4). Dotted curve is from Wagoner (1973)

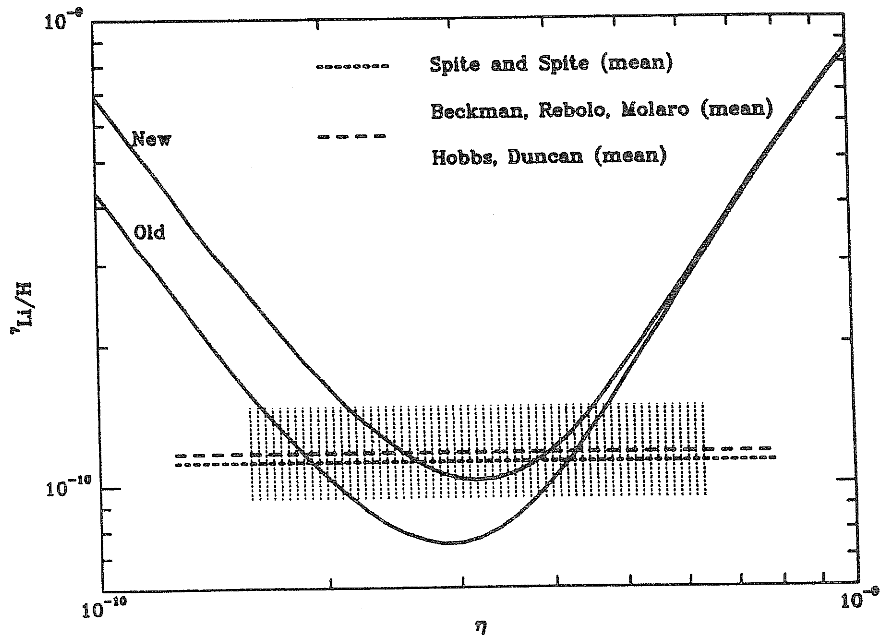
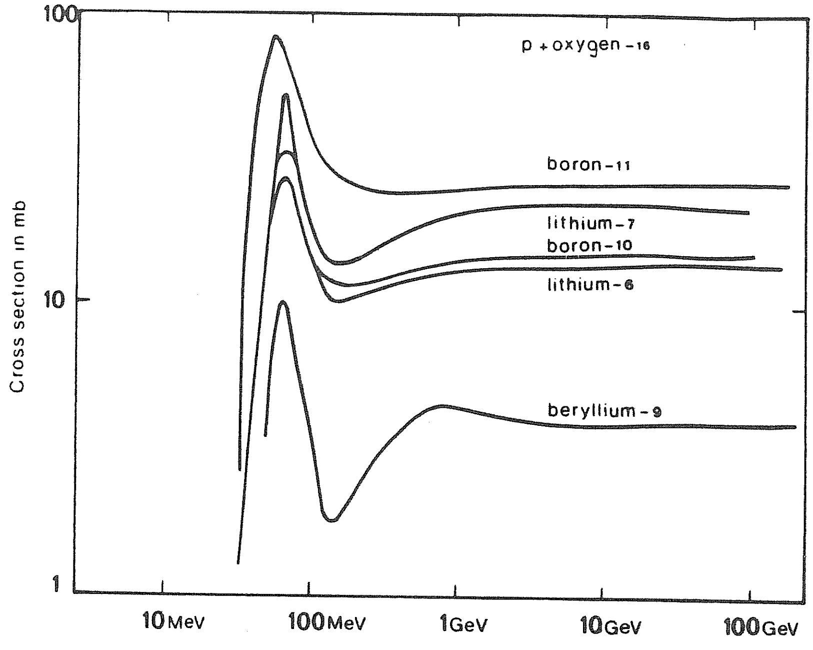


Fig 1.2 The Li/H abundance produced in big bang nucleosynthesis from Kawano et al (1987). The mean values of Spite and Spite (1982), Beckman Rebolo and Molaro (1986) and Hobbs and Duncan (1986) are shown (see the original data for details).



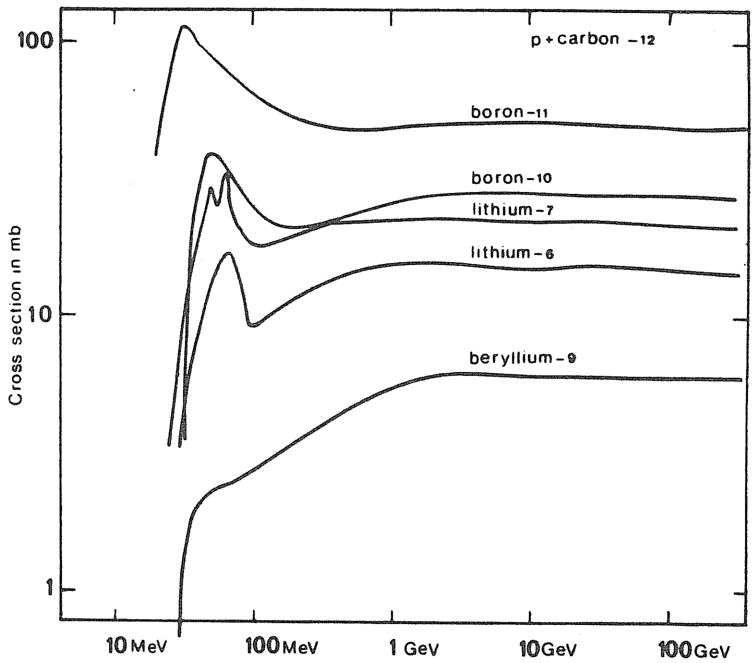
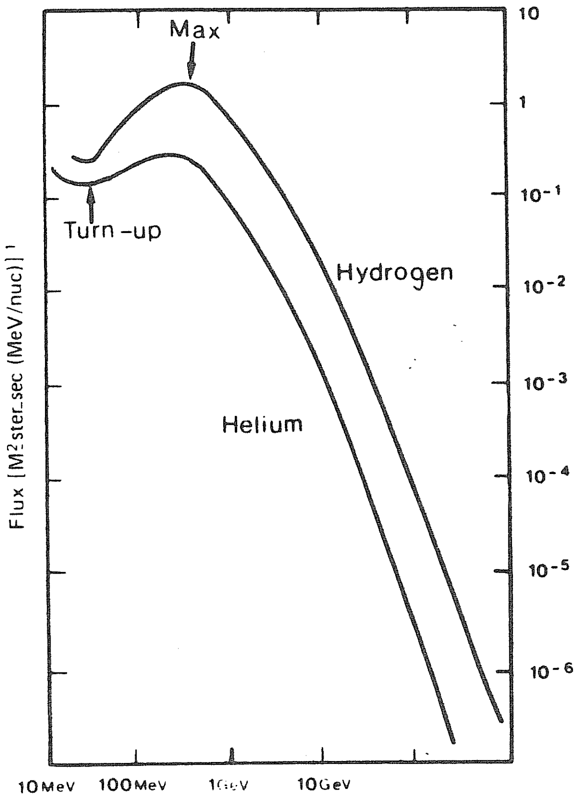


Fig 1.3 (top) and Fig 1.4 (botton). Destruction croos-section for ^{16}O (top) and ^{12}C (botton) with energetic protons from Audouze Reeves (1982).



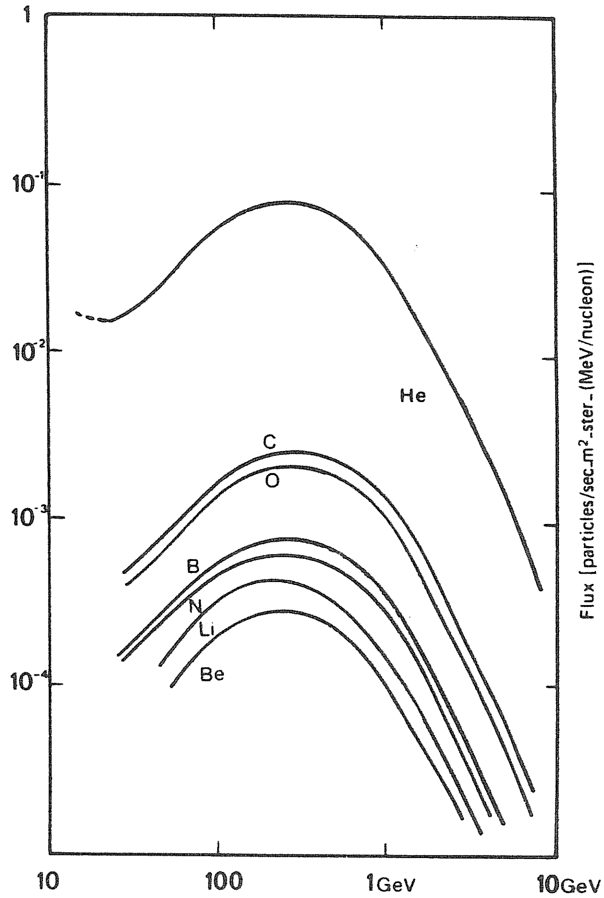


Fig. 1.5 and 1.6. The main characteristics of the galactic cosmic rays from Audouze Reeves (1982).

2. OBSERVATION OF LITHIUM IN THE POPULATION II STARS

2.1 OBSERVATION OF LITHIUM

Due to the intrinsic low amount of ^{7}Li the abundance measurements are based on the LiI resonance doublet at 6707.761 and 6707.912. The low ionization potential of lithium (P.I.=5.4 eV) implies that ^{7}Li is almost entirely ionized in stars hotter than 8000 K. The resonance line of LiII falls in the soft-x at 199A and it is virtually unobservable.

So far ^{7}Li has been determined in hundreds of stars in various stages of stellar evolution, including members of various clusters (Zappala 1972, Duncan and Jones 1983, Cayrel et al 1984). For a recent compilation of all the measurements see the review of Boesgaard and Steigman 1985).

The major problem in the interpretation of the ^{7}Li data comes from the fact that whenever, in the course of the stellar evolution, ^{7}Li is trasported to inner regions where the temperature is hot enough for (p,α) reactions (T=2x10^6 K) it is destroyed. Subsequent mixing of the outer layers with inner regions (Li-free) will globally dilute the atmospheric ^{7}Li content. Many mechanisms such as convection, overshooting, gravitational settling, turbulent diffusion, meridional circulation induced by rotation, have been proven to performed this operation. However, none of them is fully understood in the framework of the stellar structure theory.

In the solar atmosphere lithium currently amounts to N(Li)=1 about 100 times less than its supposed original main-sequence value (In this chapter we will use freely both the notations Li/H or N(Li)=[12+log(Li/H)], to conform with the literature). One or more of the above mentioned effects are held to be responsible for the strong Li depletion in the solar surface, although a convincing theoretical explanation is still lacking.

Considering the bulk of ^{7}Li determinations compiled by Boesgaard and Steigman (1985), and shown if Fig 2.1, we can draw the following considerations:

i) In the clusters (Hyades, Pleiades) the abundance curve is flat for Teff>5500 K at a value of about N(Li)=3. None of the field stars so far observed have shown values above this value.

ii) In the field stars the spread of ^{7}Li is remarkably large, of two orders of magnitude. Differences in age or a difference in the initial ^{7}Li content are both possible.

iii) The observation of ^{7}Li in the Population II "group" shows a remarkably different pattern with <u>all</u> the stars with Teff>5500 K having nearly the same ^{7}Li abundance of <N(Li)>=2.05 (Spite and Spite 1982, Spite et al. 1984).

2.1.1. Population I Versus Population II

Tha basic problem at present in interpreting the ^{7}Li amounts is establishing whether the primordial abundance was $Li/H=10^{-9}$ or $Li/H=10^{-10}$. Universality arguments can be applied to both the values and different clues have recently been advanced for both hypothesis.

Since in the Population II data all the points for Teff> 5500 K all approach the value of $1x10^{-10}$ while the points in the cooler region fall just as those of young clusters, the Spites argued that the flat curve could represent an undepleted value, reflecting the Big Bang yield. The strength of this argument is essentially statistical.

The theoretical situation with respect to the plausibility of keeping the ^{7}Li in a Population II star essentially undepleted for 10^{10} years has been recently investigated. Dappen (1984) and D'Antona and Mazzitelli (1984) have shown that convective zones become thinner and cooler at the base as the amount of metals decreases at a fixed stellar effective temperature. Michaud, Fontaine and Beaudet (1984), considering the diffusion processes, conclude that only with a highly artificial adjustement of alpha - the ratio of the mixing length to the scale height - can reproduce the observed uniformity. The Spites' assumption necessarily imply that ^{7}Li increased in the Galaxy after the formation of the Population II by one order of magnitude. This possibility has been investigated by Audouze et al (1983) and Abia and Canal (1987), who showed that red giants or novae can do the job. However if we consider the lithium meteoritic ratio, which is $2.6x10^{-9}$ when appropriately normalized to silicon, no evidence of ^{7}Li variation can be detected at least in the last $5x10^{9}$ y.

Assuming that the primordial lithium was 10^{-9} the major problem lies in finding a smooth depletion process through which ^{7}Li decreased so uniformily in the Population II stars by one order of magnitude.

Recently Boesgaard and Tripicco (1986) discovered a dib in the Li-Teff plane for middle-F stars. The dib is well defined between Teff 6400 and 6900 K and, so far, has been observed in the Hyades (Boesgaard and Tripicco 1986), NGC 752 (Hobbs and Pilachowski 1986) Coma (Boesgaard 1987), UMa group (Boesgaard, Budge and Burk 1987). The lithium observations for UMa, the Hyades and Coma clusters are shown in Fig. 2.2 from Boesgaard et al (1987). One relevant feature is that the stars on the cool side of the lithium dip seem to have less $^7Li/H$ than on the hot side, implying that depletion has already occurred in the cooler stars. For istance in NGC 752, which is 1.7×10^9 yr old, the lithium value on the right end of the dib is N(Li)=2.71, while it is 3.08 on the hotter side. Another interesting feature is the flatness of the Li-Temperature relationship between 5800 and 6400 K. Boesgaard et al. (1987) note that the flatness in the region is very reminiscent of the same flatness found in the halo stars, thus providing some empirical support to the speculation that the halo stars have indeed undergone Li depletion in the course of their long life.

At the present the situation is not clear and a cautious attitude is advisable

2.2 NEW OBSERVATIONS OF LITHIUM IN POPULATION II STARS

Given the cosmological relevance of ^7Li in the frame of the Big Bang models, we have undertaken a research programme to enlarge the sample of Li observations in halo stars, and also in those of the old disc populations to place the Li-temperature curves of Spite and Spite on a somewhat broader statistical base, to probe the effect of metallicity on lithium depletion.

2.2.1. Selection of the stars

This step was not obvious since practically all the metal poor dwarfs with spectroscopically determined metallicities reported in the Cayrel de Strobel et al. (1985) catalogue of [Fe/H] abundance determinations had already been observed by Spite and Spite (1982, 1984). We chose our stars on the basis of the photometric measurements of Carney (1983). These stars are in general fainter objects than those of the Spite and Spite sample and no spectroscopic metal abundance determinations were available. To derive the metallicity we used the Carney's calibrated relation between delta$(U-B)_{0.6}$ and the metallicity [Fe/H].

In Table 2.1 we give the basic physical parameters required to analyze the spectra of the programme stars, i.e. the effective temperature Teff, the surface gravity in the form of log g, and the metallicity with respect to the solar value $[Fe/H]=(Log(Fe/H)-Log(Fe/H)_{\odot})$.

2.2.2. Data and Data Processing

The observations were carried out at the Cassegrain focus of the 2.5 m Isaac Newton Telescope at the Observatorio del Roque de los Muchachos (La Palma, Canary Islands). The observation dates are shown in Table 2.2.

Spectral resolution was $2x10^4$ achieved using the Intermediate Dispersion Spectrograph with a grating yielding a dispersion of 9.8 A/mm. The detector was a charge-coupled device (CCD) with a

quantuum efficiency of 70% at 6700A, comprising 580 detecting elements, with an effective pixel size of 0.22 A.
The instrument gave a spectral range of 125A around the 6707 A doublet of Li. An individual spectral exposure was limited to some 20 minutes in order to limit the incidence of spurious cosmic ray induced signals. Signal to noise ratios of order of 100 were achievable for stars of magnitude m_v=10 in exposures of order of 30 minutes. For those stars which required longer exposures the spectra were co-added after independent calibration. Two dimensional inspection of the spectral images allowed us to clean the spectra of cosmic ray pulses and bad CCD columns. Each spectrum was first corrected for pre-flash, flat fielded and sky subtracted, than calibrated in wavelength using a 4th order polynomial fit, which yielded a standard error of 0.02 Å.

To be sure of our identification of the 6707 A ^{7}Li feature in spectra which were nearly featureless in the extreme cases of low metallicity we relied on a wavelength calibration routine which employed standard CuAr lamp spectra taken after each exposure. Wavelength precision was good to ±0.04, and in no cases do we subspect any ambiguity in the identification of ^{7}Li after taking into account the known radial velocity of each star.

The spectral resolution was not sufficient to resolve the doublet of Li, nor to disentangle this from the doublet of ^{6}Li (The ^{6}Li doublet is shifted by 0.16 to the red respect to the ^{7}Li wavelengths), which we have assumed of negligible equivalent width (cfr. Maurice et al. 1984). For strong indirect evidence on this we cite the upper limits derived on beryllium and boron in the population II stars discussed in the chapters 3 and 4.

In Table 2.2 we gave estimated signal to noise ratios, and in Table 2.3 the measured equivalent widths.

In Figure 2.3 we report some of the spectra illustrating the quality of the data.

2.2.3. Effective temperatures and gravities

For stars with effective temperature around 6000 K lithium is almost completely ionized. The equivalent width of the line is therefore very temperature dependent and accurate stellar temperatures are needed in order to derive accurate ^{7}Li abundances from model atmospheres.

The values of Teff used here are the results of averaging linearly the values derived from the colour indexes V-K, R-I and Stromgren b-y (see Carney, 1983) together with the value obtained from spectrophotometric scanning, if available (Peterson and Carney 1979; Carney 1983). These indices are also given in Table 2.1.

The Spites analyzed their halo dwarfs mainly with temperatures derived using the R-I index calibrated by Johnson (1966). When we have objects in common our Teff values are systematically some 100 K higher than theirs.

In Table 2.1 the values of log g are tabulated, as derived where possible from the c_1 and b-y colour indices (see Relyea and Kurucz 1978; Carney 1983. If these were not available we used the relations derived by Relyea and Kurucz (1978) between U-B, B-V and log g. We can certainly be sure from these values that all our objects are unevolved stars, mainly dwarfs, and this was confirmed by at least one of the tests applied by Carney, viz. parallax where possible or photometric index, or position in the H-R diagram.

2.2.4. Determination of lithium abundances

We used the method of spectral synthesis to derive the lithium abundances, employing LTE blanketed model atmospheres from Kurucz (1979), for values of Teff greater than 5500, or from Gustafsson et al (1975) for stars at lower effective temperatures. The models were incorporated into a spectral synthesis programme made by Castelli (1985). In this programme the transfer equation is solved with the Feautrier method as described in Mihalas (1970). The continuous opacity coefficents of HI, HeI, HeII, H^-, H_2^+, CI, SiI, MgI, AlI, and FeI and the continous scattering coefficent is the sum of Thomson and Rayleigh scattering. The total line absorption coefficent is the sum of all the line absorption coefficents in a preselected wavelength range around the line frequency. The broadening parameter is the sum of the radiative, Stark and van der Waals damping constants, which, when not known, are computed following the classical theory. For more details we refer to Castelli (1985). For continuum opacities metallicities could be varied in logarithmic steps (-1,-2,-3 with respect to solar), while individual element abundances could be varied at will.

The input parameters needed to specifie a model are the effective temperature, the surface gravity and metallicity that are discussed in the previous sections. The oscillator strengths for the ^{7}Li resonance doublet are 1.0 and 0.50, for the two lines of the doublet, taken from Wiese et al. (1966), but virtually the same as more recent measurements that include hyperfine splitting of Gaupp et al. 1982 (0.989 and 0.494, respectively). We assumed a standard value of 1.5 Km/sec for microturbulence parameter in the programme and a damping constant $CH=0.13x10^{-31}$ calculated from the Van der Waals approximation. In fact the lithium lines are generally too faint to be sensitive to the value of the microturbolent velocity and of the damping constant.

Estimation of the abundances was via equivalent width-abundance curves computed for a complete set of values for Teff, log g and underlying metallicity.

2.2.5. Errors

There are at least four independent sources of uncertainty in the lithium abundance determination:

(i) Temperature determinations. The three kinds of temperature determination used to inferr the temperature are independent, so random errors should be reduced by averaging them. A rapresentative temperature uncertainty for the present work is Teff= $\pm$80 K. which leads to an uncertainty in the ^{7}Li abundance of $\pm$0.08 dex.

(ii) Measure of equivalent widths. Determination of the equivalent widths was carried out via a standard integration routine, and errors here were due to the difficulty of assigning baselines against the combination of photon noise and readout noise present. In the best cases lower limits to the measured equivalent widths of 4 mA could be set. The errors are typically of 10% and lead uncertainties of 0.05 dex in the abundances.

(iii) Gravities. An upper limit to the error in values of log g is 0.5 dex that would lead to an abundance error of less than 0.05 dex.

(iv) Microturbulence. An uncertainty in the microturbulence parameter of 0.3 Km/sec leads to a negligible effect in the Li abundance.

(vi) Non-LTE effects. In the halo stars the large N_H/N_e ratio makes neutral atom collisions the dominant thermalizing mechanism and so non-LTE effects have negligible influence on the derived ^{7}Li abundance. In these circumstancies non-LTE effects would tend to reduce the apparent abundance derived from a given measured equivalent width of the 6708A doublet. This effect could, in the limit, be as large as 0.2 dex dex for values of Teff below 5500 K, but is unlikely to be greater than 0.05 dex at the upper end of our temperature range. Anyway this would apply to all ^{7}Li determinations in halo dwarfs. For a more detailed discussion the reader is referred to Steenbock and Holweger (1984). A finer quantitative estimate of the effect must await improved collision cross-section for H atoms.

A comparison of the present ^{7}Li abundance determinations with those of the Spites (1982,84,86) for the objects in common shows our values are higher with a mean difference of 0.1 dex. This is essentially due to the different Teff calibration adopted, which as explained in section 2.2.3 gives some 100 K higher values in our case.

2.3. THE LITHIUM ABUNDANCE IN THE EXTREMELY METAL-DEFICIENT DWARF G 64-12

In this section we describe the ^7Li abundance determination in the dwarf G64-12 which is the most metal deficient dwarf so far reported (Carney and Peterson, 1981) with [Fe/H]=-3.5. A small number of stars with probably lower metallicities have more recently been reported Beers et al. (1985), but they did not make quantitative estimates of their metallicities, and are too faint to be observed with the present telescopes with the adeguate resolution for ^7Li observations. G64-12 is also the warmest halo dwarf in which ^7Li has been detected. The star's very high velocity V_{rad}=439 Km/sec (Carney and Peterson, 1981) implies that it was almost certainly formed tens of Kpc away from the galactic plane. This star is an excellent candidate for enhancing our knowledge of primordial lithium.

2.3.1. Observations

The observations were performed on the nights of 28th and 29th July, 1986 at the Cassegrain focus of the Isaac Newton Telescope (2.5m) of the Observatorio del Roque de los Muchachos. It has been used the same set-up of the other ^7Li observations (see previous sections)
We obtained 5 spectra in all, for this V=11.5 mag. star, 3 on the first night and 2 on the second with exposure of 20 minutes each (longer exposures would entail excessive cosmic rays pulses in the CCD chip, and shorter would give poor signal to electronic read-out noise ratio). Finally the spectra were co-added yielding a signal to noise ratio of about 100.
The spectrum in the Lithium region is shown in Figure 2.4.
Within our wavelength range only one line was detectable in

absorption and taking into account the radial velocity of the star this was unequivocably identifiable as the Li doublet. Its equivalent width was measured at 23 mA, with a conservatively estimated uncertainty in the range 20%.

The star was observed, nearly simultaneously by Spite et al. (1987) and they found an equivalent width of 20-30 mA in good agreement with our independent estimation.

2.3.2. ^{7}Li abundance

To derive the ^{7}Li abundance we employed the same method as for the other stars. Teff was estimated from the photometric indices V-K, R-I and b-y, calibrated against metallicity, from Carney (1983). The resulting value for Teff is 6230 K. The dereddening correction for the star, which is at a distance of 230 pc, gives a definitive effective temperature of 6350 K (see Carney and Peterson 1981) with an uncertainty of +/-75K.
From the values of b-y and c, of Carney (1983) we inferred a value for log g of 4.0, and we took the metallicity of -3.5 directly from Carney and Peterson (1981).
The lithium abundance was computed using two parameters sets: a) Teff=6250, log g=4.0, [Fe/H]=-3 and b)Teff=6350, log g=4.0, [Fe/H]-3.0. The resulting ^{7}Li abundance, Log N(Li) was found to be 2.16 and 2.23 for Teff=6250, and 6350 respectively.
This shows also that an error of 100 K would lead to an error of 0.07 dex in the ^{7}Li abundance. We have verified that the 20% uncertainty in the equivalent width measured leads to un uncertainty of 0.1 in dex in the derived ^{7}Li abundance. Taking into account these errors, and the less significant errors due to the uncertainty in log g, we estimate a global

figure for the uncertainty in LogN(Li) of 0.2 dex.
Adopting the de-reddened value of Teff we therefore find the ^{7}Li abundance in G 64-12 to be 2.23(±0.20). The remarkable fact about the lithium abundance in G 64-12 is that its value is vrey close to that found in previously measured metal deficient stars of population II.

2.4. DISCUSSION OF THE NEW LITHIUM ABUNDANCES

In Figure 2.5 we show all the ^{7}Li abundances obtained in the present study, plotted against temperature. The data points have a scatter larger than the original points of Spite and Spite (1982) going from N(Li)=1.9 to 2.4. This scatter is larger than the estimated errors thus it should reflect an intrinsic dispersion of the lithium abundance. Anyway we note that the original result of Spite and Spite (1982) can be preserved considering only the more-metal deficient stars. We have drawn a distinction between "extremely metal-deficient" (EMD) stars, which we define as stars with [Fe/H]<-1.4, and the other "highly metal-deficient" (HMD) stars whith [Fe/H] in the -1.4 to -0.4 range. Without drawing physical conclusions about the reasons for the increasingly scattered ^{7}Li abundances for [Fe/H]>-1.4 at this stage, we use this value as an empirical border line. Considering only the EMD stars the ^{7}Li abundance appear again remarkably constant as can be seen from Fig 2.6.

A thorough consideration of the data in Figure 2.6 highlights the following points:

1) For stars with [Fe/H]<-1.4 there is relatively little spread in log N(Li), with all values lying between 1.9 and 2.25. Within this metallicity range the lithium abundance increases slightly as the effective temperature raises. Thus the constancy found originally is confirmed now for a total of some 30 population II stars, significantly larger than the original sample, but more important, still, we have now a sample with a larger variety of physical properties such as metallicity, kinematics and temperatures.

We have extended considerably the metallicity range in which very little variation of logN(Li) is observed. This range is now -1.3/-3.5. G 64-12, with metallicity -3.5, is more metal-deficient than any known globular cluster. Two others of our stars have metallicities lower than [Fe/H]=-3, approaching the most metal deficient dwarf G 64-12. These are HD 140283, with [Fe/H]=-3, Magain 1985, measured both here and in the Spite and Spite (1982), and BD 3° 740, whose ^{7}Li has been determined here for the first time. Our metallicity determination sets an upper limit of [Fe/H]<-2.3 for this star but a very recent determination by Magain (1987), using stronger Fe lines, gives [Fe/H]=-3.13 making it the second most metal-poor dwarf so far measured for lithium.

The observed constancy over such a wide metallicity range tells against any significant galactic production of ^{7}Li in the early stages of the galacticevolution in which this metallic enrichment took place.

We have included in the sample stars with extreme kinematical properties. In Table 2.2 we have listed the kinematical properties of our programme stars. According to

Sandage and Fouts (1987) a star can be considered as belonging to the halo population if it meets either Vrad>100 Km/sec or W>60 Km/sec. All the stars which we have termed EMD conform to at least one of these criteria. Of the HMD stars, some in fact meet these criteria and some do not, as for example BD 18 3423. Thus it appears that the processes governing lithium depletion depend more critically on the metallicity than on the kinematical distinction between halo and disc. However, among the extreme metal-deficient stars some have very high velocities as BD 17 4708 (-295 Km/sec), BD 2 3375 (-392 Km/sec), BD 72 94 (-266 Km/sec) and G64-12 (439 Km/sec).

The uniformity of lithium in these stars is significant because they are believed to have been formed at great distances from us and from one another (in the order of kiloparsecs), thus reducing the probability of the uniformity being a purely local effect. This favours a cosmological origin for lithium rather than an origin due for example to interstellar spallation by cosmic rays from early supernovae or even production in pre-galactic supermassive objects (Norgaard and Fricke, 1976).

We have observed the hottest star of the sample and this is particularly important since depletion processes decrease as the temperature increases, as it has been pointed out by Boesgaard (1986). Considering G64-12 we can state that for effective temperatures between 5500 K and 6350 K the abundance of lithium in the Population II varies by a factor lower than 2. For comparison the ^{7}Li abundances in young objects such as the Hyades (Cayrel et al. 1984), within a comparable temperature range, varies by a factor close to 40. It would be now even more surprising if strong depletion had produced the presently observed uniformity in the lithium abundance over in the quoted temperature range (i.e mass range).

2) The two stars BD 66 268 and BD 38 4955 are worth noting because they are the most metal deficient ([Fe/H]=<-2.5 and [Fe/H]=-2.5 respectively) measured for lithium in the Teff range below 5500 K where depletion clearly has occurred in the halo dwarfs has shown in Spite and Spite (1982). Our upper limits in these stars show that however metal deficient may be the star, lithium depletion is effective at these temperatures. For comparison HD 64090, which has [Fe/H]=-1.9 is a little warmer and has a measurable Li abundance of Log N(Li)=1.7.

3) For -1.4<[Fe/H]<-1.0 a characteristic value of log N(Li) is close to 2. However, there is much more scatter than for the EMD stars, with a maximum value of log N(Li) at 2.4, and with several warmer stars in this sample having log N(Li) below 1.5. For temperatures above Teff=6000 K there is a tendency for the EMD stars to show less lithium than the HMD. Some HMD stars (HD 208906, BD 18 3423) have Li abundances in the range 2.35-2.40, a little higher than those of EMD stars in the same Teff range, i.e.>6000 K.

Below 5700 K this situation is reversed and HMD stars have lower ^{7}Li abundances than the EMD. In general for both sets of objects the cooler stars in the observed range show lower abundances, in accordance with generally accepted ideas about the dependence of ^{7}Li depletion rates on the depths of convection zones.

4) One somewhat puzzling case is that of HD 221377 for which we took Teff=6000 K (Sneden, 1979) and Log g=3.5. We measure a metallicity [Fe/H]=-1.3 for this star, in fair

agreement with Sneden (1979) who found -0.9. However the ^{7}Li abundance is very low, <1.45, and such a low value for these values of Teff and [Fe/H] has only one previous counterpart in metal poor stars: HD 97916 (Spite et al 1984). We must point out that with the photometric colour indices at our disposal (Bond 1970), and following our usual proceedures, we infer Teff=6450 K, which is much higher than Sneden 's estimate. This would put HD 221377 into the "Lithium gap" observed by Boesgaard and Tripicco (1986b) in the Hyades and field hot F dwarfs, which is a possible explanation for the absence of detectable Li.

If this is the case this should be regarded as the first evidence that also in the Population II stars a dib like that observed in the young clusters could be present. However it is rather difficult, if not impossible, to find halo dwarfs hotter than Teff=6400 K due to the relatively shorter main-sequence life times and the presence of such a dib can only be postulated.

2.4.1. Comparison with lithium observations

In Figure 2.7 we present ^{7}Li abundances versus metallicity compiled assembling the data in the literature for stars with Teff>5500 K.

For our own stars we have quoted the precision of the determined abundances. However the sample as a whole is not homogeneous, so error limits to the abundance determinations may vary, typically, in the range 0.1-0.2 dex both for ^{7}Li and Fe.

As we have alredy seen for stars with [Fe/H]<-1.4 there is relatively little spread in log N(Li), with all values around 2.0, but with a small rise in Li abundance with effective

temperature, shown more clearly in Figures 2.2 and 2.4.
For $-1.4<[Fe/H]<-1.0$ the characteristic value of log N(Li) remains close to 2. However, there is much more scatter than for the EMD stars, with a maximum value of log N(Li) at 2.4, and with some warmer stars having log N(Li) below 1.5.
For $[Fe/H]>-1.0$ there is a very wide scatter of ^7Li abundances at all metallicities, with a tendency for upper envelope of ^7Li abundance to rise to higher metallicities, while below this envelope appear stars with the whole range of measurable ^7Li abundances.

The presumption is that above $[Fe/H]=-1.4$ the dividing line significant enrichement by galactic processes may have occurred.

2.4.2. Comparison with the lithium in the Hyades

In Figure 2.8 we show log N(LI) against Teff for EMD in the literature against the same plot for Hyades from data of Cayrel et al. (1984) and of Duncan and Jones (1983). The Hyades is fairly young cluster, with an estimate age $8x10^8$ years (Partenaude, 1978). From the figure it is possible to see that for Teff<5600 the Li abundance in the Hyades is less than in the EMD stars. This indicates that, if the EMD stars were formed with a comparable abundance of initial lithium to the Hyades (Log N(Li)=3), then their ^7Li depletion in absolute terms has been less. Since they are of order ten times older, their effective depletion rates would have been, in this temperature range, at least ten times lower than those of the Hyades. At Teff=5500 K, for example, this factor is at least twenty.

From the observations presented above and in the literature we know that for all open cluster so far observed the depletion increases as Teff decreases in the range Teff<6300 (Duncan and Jones, 1983; Cayrel et al 1984; Hobbs and Pilachowski 1986; Spite et al 1987). In the Hyades for Teff between 6000 K and 6300 K the depletion has been slight or negligible as it can be deduced from the fact that their Li abundances are close to that found in the meteorites (Reeves and Meyer 1978) or the even younger Pleiades (Duncan and Jones, 1983). If the EMD stars were formed with log N(LI)=3, than as we explained above at Teff<5500 K the mean depletion rate is at least ten times lower than that for the Hyades. On these basis we deduce that the rate of depletion of the EMD stars between 6000 and 6300 K should have been at least ten times slower than the depletion rate for the Hyades between the same Teff values. Hence we conclude that the total ^{7}Li depletion in EMD stars between 6300 K and 6000 K has been negligible, and therefore the initial abundance was very near to that which is now observed.

Here we have not taken granted any particular mechanism or set of mechanisms for ^{7}Li depletion, nor do our conclusion depend critically on whether this has occurred while stars were on the main sequence or in the pre-main sequence phase. It is worth noting, however, that the theoretical study of D'Antona and Mazzitelli (1984), in which for EMD stars the depletion turns out to be essentially during the pre-main sequence phase and whose theoretical curves do show good fits to the observations of Fig. 2.4, predicts that such stars with temperatures above 6000 K should be essentially undepleted, in accord with our more empirical inference. This conclusion (which essentally is the same as that reached by the SS) cannot be regarded as beyond dispute, but is backed by considerable circumstantial evidence.

2.5 LITHIUM AS A COSMOLOGICAL PARAMETER

The detection of lithium in the Population II stars has provided, for the first time, strong evidence for a pregalactic origin of at least a fraction of the lithium present today in the universe. This evidence is basically independent of the possibility of some depletion and rests on the fact that the EMD stars have such low metallicities that they must have been formed in a very early epoch of the Galaxy (Cayrel 1986), before significant enrichment of ^{7}Li could occur in the material which went into their formation. The most plausible alternative ways to produce lithium in relevant quantities such as novae and red giants, require longer time scales than the time elapsed before the formation of the Population II stars.

The consequent cosmological deductions on the universal mean baryon density, and the influences on the number of permitted neutrino types have been by now well examined in the literature (see A.M. Boesgaard and G. Steigman 1985). We will consider here again this matter on the light of the new lithium-eta curves provided by the recent computations by Kajino et al (1987) and Kawano et al (1987), with particular regard to the estimated uncertaintes by Kajino et al (1987).

2.5.1. The baryon density

Measuring primordial ^{7}Li is a particularly accurate way to determine the baryon-to-photon number at the epoch of primordial nucleosynthesis, since the lithium yield is essentially independent from the rate of expansion of the universe unless this is increased by a very large factor. Also the other primordially produced light elements D and ^3He show strong dependence on baryon-to-photon value, but they can reliably used only if one can extrapolate the observed abundances effectively in order to obtain the primordial values. For both D and ^3He the determination of the present values is controversial and the likely effects of the galactic evolution might not be well understood.

Observing ^7Li in Population II objects provides the opportunity of a direct measurement of a primordial light element, the only uncertainty coming from a possible depletion. In particular a safe upper limit on the primordial lithium makes it possible to set lower limits to the baryon-to-photon number. Considering that possibility of some lithium being depleted in the atmospheres of old stars is still open Boesgaard and Steigman (1985) took into account the situations both with and without depletion.

Here we follow the same line of thinking but with a slightly different interpretation of the lithium data in the Population II stars. We assume here that no appreciable depletion (or less depletion) has occured in the stars above 6200 K. Essentially instead of consider all the stars we consider only the hotter stars. This is supported by theoretical considerations (D'Antona Mazzitelli (1984) and by observations of the population I field stars and open clusters. HD 84937 (Boesgaard 1985), HD 74000 (Spite and Spite, 1986) and G64-12 are giving a good approach to a primordial ^7Li estimate. This value is

2.18 with an internal scatter of ± 0.03 dex. We note that if we include also the hotter HMD stars HD 208906, BD 18 3423 and HD 3567, that have lithium abundances 2.40-2.35 and 2.35 respectively, the average value for lithium increases further. From the present work we can select 8 stars with Teff> 5900 K and [Fe/H]<-1.2 that, together with HD 74000 and HD 84937, give a $\langle N(Li)\rangle = 2.20$ with an internal scatter of ± 0.07 ($Li/H = 1.6(\pm 0.25) \times 10^{-10}$). We consider this value coming from the hottest stars as more close or certainly a more reliable lower limit of the primordial value than the one derived from the totality of the Population II stars with Teff>5500 K. This suggestion must remain tentative pending a significant increase in the number of the Li measurements in the hot stars.

This small upward revision of the value derived by Spite and Spite (1982) and Spite et al (1984) has in fact deep implications on the baryon density that can be derived from lithium observations in the framework of the standard big bang model. The new values regardless depletion are:

$$1.6(\pm 0.25) \times 10^{-10} < {}^{7}Li/H < 8 \times 10^{-10}$$

For the upper limit we have deducted the fairly well established production by spallation of high energy GCR, i.e. an estimated 2×10^{-10}, from the measures of beryllium and boron.

The new minimum value for Li of Kajino et al (1987) is about 0.85×10^{-10}, that taking into account the theoretical uncertainties of 35% raises to 1.15×10^{-10}. If we compare this result with the new observational lower limit placed above we found that it remains above (within two σ) of the minimum amount of lithium allowed in the primordial nucleosynthesis. Thus two different ranges for eta are allowed $0.65-2.5\times10^{-10}$ and $3-10\times10^{-10}$. If we consider the value 1.6×10^{-10} as the true primordial value, the two ranges become very small $1.3-2.5\times10^{-10}$ and $3-4.5\times10^{-10}$.

The $0.23<Yp<0.24$ value recently reported by Pagel (1986) for Yp - the mass fraction of primordially produced ^{4}He- in the strict context of classical Big Bang nucleosynthesis implies a baryon-to-photon number lower than 3×10^{-10} (for a number of species of light neutrinos N=3) and a $\tau>10.2$ minutes neutron half-life. We note that in this contest Yp favours low values of the baryon-to-photon number while conflicting with the second possible range of values for the baryon-to-photon number. However, the low figures of the baryon-to-photon number have to be compared with the lower limit of $3-4\times10^{-10}$ derived using the D+^{3}He argument (Boesgaard and Steigman 1985).

The value of the baryon-to-photon number at the time of nucleosynthesis can be related with the present nucleon mass density by the following relation:

$$\rho_0 = M_N \eta n_{\gamma 0}$$

where $n=399(T/2.7)^3=399\theta^3$ cm^{-3} is the present number density of relic photons and T is the present temperature of the microwave background radiation. The critical density is:

$$\rho_{c0} = \frac{3 H_0^2}{8\pi G}$$

where $H_0=100h_0$ Km/sec. We obtain

$$\Omega \equiv \frac{\rho_N}{\rho_c} = 0.0035\, h_0^{-2}\, \theta^3\, \eta_{10}$$

Thus with the baryon-to-photon number lower than 2.5×10^{-10}, T=2.7, we have OMEGA<0.009 for h=1, and OMEGA<0.035 for h=0.5. The baryonic cosmological deduced from our analysis is significantly smaller than the one of Yang et al. (1984) who derived OMEGA lower than 0.19 and smaller than the value deduced from large scale dynamics (>0.20) implying that a large fraction of the matter present in the Universe should be in a non-baryonic form.

2.4.2. The number of neutrino types

To assess the number of neutrino types in the framework of the standard big bang model, we must know Yp and the baryon-to-photon number, a minor role being played by the uncertainty on the half-life of neutron. Since the He yield increases with the number of light particles and with the increase of the baryon-to-photon number, to constraint the number of light particles we need an upper limit to Yp and a lower limit to eta (and a lower limit to the neutron half-life). The dependence of the helium yield on these parameters is illustrated by the relation (Boesgaard and Steigman 1985):

$$Yp=0.230 + 0.011 \mathrm{Ln}\, \eta_{10} + 0.013(N-3) + 0.014(\tau - 10.6)$$

Taking the last determination for Yp<0.24 (Pagel 1987), for eta>0.65, that corresponds to $Li<8 \times 10^{-10}$, we obtain N<4.13, and for eta>1.5, that follows from $Li=1.8 \times 10^{-10}$, we obtain N<3.43.

STAR	m_V	DATE	EXPOS (sec)	S/N	Vr	U	V	W	e	REF
HD 3567	9.25	1	600	80	-49	-187	-330	-78	0.84	E
			850							
			500							
HD 19445	8.05	1	1000	160	-143	-158	-118	-57	0.62	E
HD 64090	8.27	2	400	90	-235	-257	-161	-93	0.85	C
HD 114762	7.30	4	600	200	46	56	- 50	54	0.24	S
HD 123710	8.21	4	400	200	7	——	——	——	——	C
			300							
HD 132475	8.52	1	1200	110	174	- 56	-177	80	0.69	E
HD 140283	7.24	1	1200	130	-171	215	-169	- 6	0.78	E
HD 160693	8.41	4	1200	200	36	-137	- 41	64	0.44	C
HD 184499	6.62	4	400	380	-165	52	-145	58	0.62	C
HD 193901	8.67	1	600	140	-175	154	-180	-19	0.75	E
HD 195633	8.56	2	600	90	- 69	74	- 34	0	0.22	B
HD 200580	7.32	1	600	150	4	-102	- 56	19	0.38	E
HD 201889	8.05	1	1000	140	-103	110	- 66	-18	0.43	C
HD 201891	7.30	1	300	100	- 45	- 92	-116	-61	0.52	E
			600							
HD 204613	8.31	4	600	180	-112	20	-97	-108	——	E'
HD 208906	6.94	4	300	300	8	- 73	- 2	-10	——	E'
HD 216777	8.01	4	600	150	- 23	99	-53	-33	0.24	E"
HD 218209	7.49	4	360	150	——	53	- 30	- 5	0.20	SY
HD 219617	8.17	1	1200	150	10	-298	-255	-44	0.99	E
HD 221377	7.57	4	300	180	——	——	——	——	——	B
BD-10° 388	10.37	2	1000	100	37	257	-112	56	0.75	BM
			1000							
			1000							
			1200							
BD 2° 3375	9.92	1	1200	110	-392	356	-233	41	0.98	E
BD 3° 740	9.81	2	1000	100	176	117	-321	21	0.82	E
BD 4° 4551	9.61	2	1200	70	-118	90	-60	59	0.31	B
BD 7° 4841	10.37	2	1000	65	-231	153	-239	27	0.92	E
			600							
BD 9° 352	10.17	2	1000	70	- 68	69	-127	126	0.47	S
			1000							
BD 17° 4708	9.47	1	1200	130	-295	352	-286	17	0.99	E
			1200							
			1200							
			1200							
BD 18° 3423	9.79	2	800	55	-242	33	-280	-43	0.94	E
BD 23° 3912	8.90	1	1200	150	-115	38	-104	59	0.40	B
BD 26° 2606	9.72	1	1200	160	32	-115	-111	18	0.53	E
			1200							
BD 29° 366	8.76	1	1200	160	28	75	-148	-90	0.59	S
BD 29° 2091	10.24	3	1000	70	74	-105	-246	83	0.94	E
BD 38° 4955	11.10	1	1200	140	- 32	11	- 37	-28	0.18	C
			1200							
BD 42° 2667	9.87	1	1200	100	-157	-106	-211	-46	0.79	SY
BD 59° 2723	10.47	2	1000	80	-103	224	-206	-64	0.86	S
BD 66° 268	9.91	1	600	60	-160	154	-392	-60	0.58	SY
BD 72° 94	10.20	2	1000	80	-266	-316	-111	+35	——	S

NOTES

Date 1: 6-8/8/85
Date 2: 2/10/85
Date 3: 16/3/86
Date 4: 28-29/7/86

Vr: radial velocity
U, V, W: space motion
e: eccentricity of galactic orbit

B : Bond (1970)
BM: Bidelman and MacConnell (1973)
C : Carney (1978)
E : Eggen (1979)
E': Eggen (1972)
E": Eggen (1969)
S : Sandage (1969)
SY: Saio and Yoshii (1979)

Table 1. Log of the observations and kinematical properties of the stars

Star	V-K	R-I	b-y	c_1	T_{eff}(K)	log g	[Fe/H]	REF
HD 3567	1.35	0.33	0.330	0.278	5950	4.0	(-1.0)	1
HD 19445	1.39	0.35	0.349	0.200	5830	4.5	-2.4	2
HD 64090	1.73	0.41	0.431	0.147	5350	4.0	-1.9	3
HD 114762	----	0.35	0.357	----	5740	4.0	-0.79	4
HD 123710	1.49	0.35	----	----	5740	4.0	(-1.1)	1
HD 132475	1.63	0.38	0.386	0.358	5550	3.8	-1.0	3
HD 140283	1.59	0.36	0.377	0.311	5640	3.5	-3.1	2
HD 160693	1.51	0.35	----	----	5710	4.0	-0.69	5
HD 184499	(1.34)	0.36	0.390	0.314	5610	4.0	-0.66	4
HD 193901	1.52	(0.31)	0.371	0.210	5690	4.0	-1.24	12
HD 195633	1.38+	0.31*	0.386	0.352	5840	3.8	-1.10	6
HD 200580	1.47+	0.35	0.363	0.183	5730	3.5	(-0.8)	1
HD 201389	1.51	0.37	----	----	5580	4.0	(-0.3)	1
HD 201891	1.42	0.33	0.348	0.260	5850	4.5	-1.4	7
HD 204613	----	----	0.403	0.294	5590	3.5	-0.30	8
HD 208906	1.35	0.32	0.336	0.288	5960	4.0	-0.70	9
HD 216777	1.60	0.38	0.400	0.275	5540	4.0	(-0.4)	1
HD 218209	1.62	0.38	----	----	5500	4.0	(-0.4)	1
HD 219617	1.39	0.33	0.342	0.214	5870	4.5	-1.40	5
HD 221377	----	----	----	----	6000	3.5	-0.9	10
BD-10° 388	1.33+	0.32	----	----	5980	3.5	-2.2	11
BD 2° 3375	1.46	0.35	0.349	0.317	5820	4.0	-2.55	12
BD 3° 740	1.31	0.29*	0.307	0.434	6140	3.5	-3.13	13
BD 4° 4551	1.49	----	0.371	0.319	5670	3.7	-1.76)	12
BD 7° 4841	1.39	0.32*	0.344	0.352	5920	4.0	(-1.1)	1
BD 9° 352	1.42	----	0.343	0.240	5870	4.5	-2.08	12
BD 17° 4708	1.40	0.34	0.325	0.338	5890	4.0	-1.95	14
BD 18° 3423	----	0.30 0.29*	----	----	6140	4.0	-1.00	14
BD 23° 3912	1.45+	0.36	0.362	----	5720	4.0	-1.60	12
BD 26° 2606	1.37	0.33	0.328	0.280	5980	4.5	-2.58	12
BD 29° 366	1.55	0.39	0.389	0.335	5560	3.3	(-1.2)	1
BD 29° 2091	1.50	----	0.374	0.243	5670	4.5	-1.73	12
BD 38° 4955	1.93	0.46	0.473	0.097	5080	4.5	(-3.0)	1
BD 42° 2667	1.36	0.34	0.333	0.280	5960	4.0	-1.45	14
BD 59° 2723	1.42	----	0.356	0.280	5330	4.0	(-1.9)	1
BD 66° 268	1.34	0.43	0.442	0.165	5240	4.0	-2.10	12
BD 72° 94	(1.50)	0.29*	0.309	0.263	6160	4.5	-1.62	12

Table 2.2 Photometry and basic stellar parameters. Photometry sources: Carney (1983), Bond (1970), Eggen (1973,1979). * indicates (R-I) derived from$(R-I)_K$ through the relation given in Eggen (1973) The measurements in the Kron system are taken from Eggen (1979). + indicates (V-K) taken from Arribas and Martinez-Roger (1987). Photometric indeces in parenteses have not been considered. Metallicities in parentheses are photometrically estimated. Ref: 1) Carney (1979,1983); 2) Magain (1984); 3) Hernshoaw (1976); 4) Peterson (1981); 5) Wallerstein (1962) 6) Sneden (1974); 7) Carney (1979); 8) Sneden et al (1976); 9) Clegg (1977); 10) Sneden et al (1979); 11) Barbuy et al (1985); 12) Tomkin et al (1986); 13) Magain (1987); 14) Peterson (1980)

STAR	Fe I 6663.45	Fe I 6677.99	Fe I 6750.15	LI I 6707.8 A
HD 3567	23	53	18	45
HD 19445		20		35
HD 64090	16	63	11	10
HD 114762	50	84	39	25
HD 123710	68	104	58	23
HD 132475	21	57	18	52
HD 140283	—	14	—	50
HD 160693	69	100	47	<4
HD 184499	71	97	46	9
HD 193901	34	67	29	30
HD 195633	59	89	35	40
HD 200580	59	100	43	32
HD 201889	55	79	33	5
HD 201891	34	67	22	27
HD 204613	81	104	53	<6
HD 208906	43	77	31	50
HD 216777	89	127	59	19
HD 218209	84	126	59	<6
HD 219617	15	43	13	40
HD 221377	28	69	16	<6
BD-10° 388	—	10	—	35
BD 2° 3375	—	<8	—	30
BD 3° 740	—	<8	—	21
BD 4° 4551	16	44	—	29
BD 7° 4841	24	55	—	37
BD 9° 352	—	14	—	34
BD 17° 4708	—	36	—	25
BD 18° 3423	33	65	24	34
BD 23° 3912	18	61	15	73
BD 26° 2606	—	<7	—	35
BD 29° 366	43	80	36	14
BD 29° 2091	—	20	—	45
BD 38° 4955	8	20	—	<8
BD 42° 2667	10	32	—	28
BD 59° 2723	—	28	—	25
BD 66° 268	—	<10	—	<10
BD 72° 94	—	20	—	27

Table 2.3 Measurements of equivalent widths.

Star [Fe/H]<-1.4	T_{eff}	[Fe/H]	Log N(Li)
BD 72°94	6160	-1.8	2.22
BD 3°740	6110	<-2.3	2.13
BD 26°2606	5980	<-2.2	2.24
BD 42°2667	5960	-1.7	2.12
BD-10°388	5950	-2.2	2.18
BD 17°4708	5890	-1.7	1.98
HD 219617	5870	-1.5	2.20
BD 9°352	5870	-2.2	2.12
HD 19445	5830	-2.2	2.05
BD 59°2723	5830	-1.6	1.95
BD 2°3375	5820	<-2.5	2.00
BD 29°2091	5670	-2.1	2.10
BD 4°4551	5670	-1.7	1.88
HD 140283	5640	-2.5	2.03
HD 132475	5550	-1.6	2.05
HD 64090	5370	-1.9	1.17
BD 66°268	5240	<-2.5	<1.10
BD 38°4955	5080	-2.5	<0.80
-0.6≥[Fe/H]≥-1.4			
BD 18°3423	6140	-0.8	2.35
HD 221377	6000	-1.1	<1.45
HD 208906	5960	-0.9	2.40
HD 3567	5950	-1.2	2.35
BD 7°4841	5900	-1.2	2.24
HD 201891	5850	-1.0	2.08
HD 195633	5780	-0.9	2.15
HD 114762	5760	-0.8	1.88
HD 200580	5740	-0.7	2.00
HD 123710	5740	-0.6	1.85
BD 23°3912	5720	-1.3	2.40
HD 160693	5710	-0.7	<1.0
HD 193901	5690	-1.2	1.95
HD 184499	5610	-0.8	1.28
HD 204613	5590	-0.7	<1.00
HD 201889	5580	-1.1	0.90
BD 29°366	5560	-1.1	1.40
HD 216777	5540	-0.6	1.54
HD 218209	5500	-0.6	<1.00

Table 2.4 Lithium and iron abundances

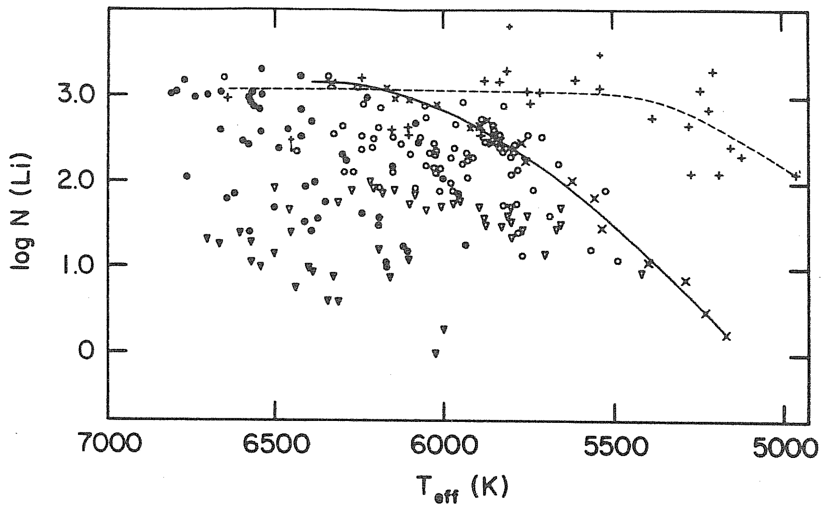


Figure 10 Lithium abundances in Pop I stars plotted [on the scale where log N(H) = 12.00] as a function of stellar effective temperature. The solid circles are from the survey of F0–F5 field dwarfs of Boesgaard & Tripicco (1985), and the open circles are Duncan's (1981) survey of F5–G5 field dwarfs; open and filled triangles represent upper limits from the respective surveys. The crosses (×) are from the Hyades results of Cayrel et al. (1984) (large crosses) and Zappala (1972) (small crosses), the latter as reanalyzed by Duncan & Jones (1983). The solid line shows the curve of Li depletion with stellar mass for the Hyades. The plus symbols are for the Pleiades dwarfs from Duncan & Jones (1983), with the larger symbols representing higher-quality data. The dashed line is an uncertain curve of Li depletion with stellar mass for the Pleiades. Large depletions of Li can be seen, but the maximum is uniform over a temperature range of 1500 K.

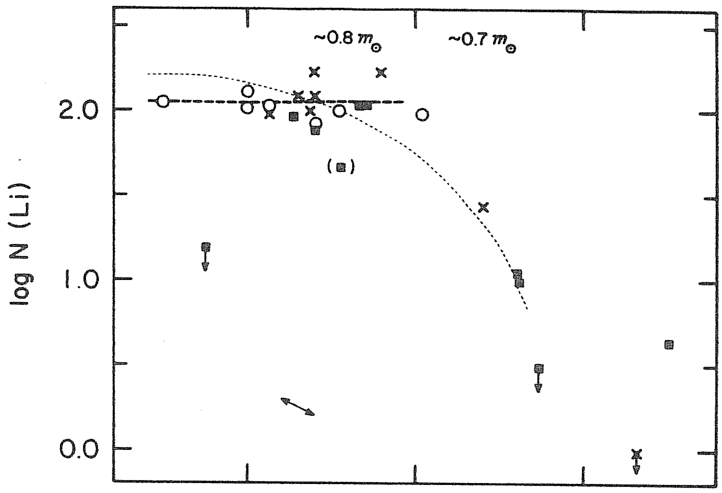


Figure 11 Lithium abundances in Pop II stars [with log N(H) = 12.00] as a function of stellar effective temperature. The different symbols represent different [Fe/H] abundances: open circles $\leqslant -2.0$; crosses -1.5 to -2.0; filled squares $\geqslant -1.5$. The horizontal dashed line is the mean of the upper points. Arrows on the points indicate upper limits. The square in parentheses is an uncertain determination caused by a cosmic-ray event near the Li line. The light dashed curve shows the pre-main-sequence Li depletion calculated by D'Antona & Mazzitelli (1984) for an initial value of log Li = 2.2. The arrow in the lower left shows the effect of a temperature change of 100 K on the derived Li abundance. (After Spite et al. 1984.)

Fig 2.1. From Boesgaard and Steigman 1985. Compilation of lithium observations

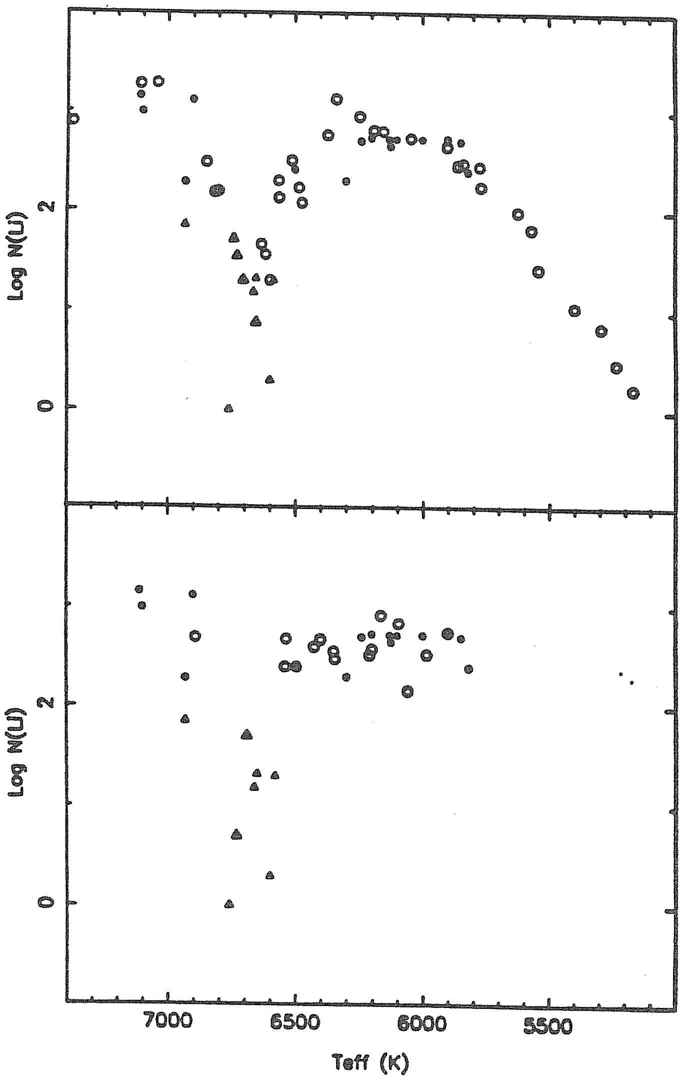


Fig 2.2 LogN(Li) for UMa (solid symbols) compared with the Hyades (open circles) in the upper panel and Coma (open circles) in the lower panel. Both open and filled triangles represent upper limit values. From Boesgaard et al (1987) Lihtium observations in NGC 752.

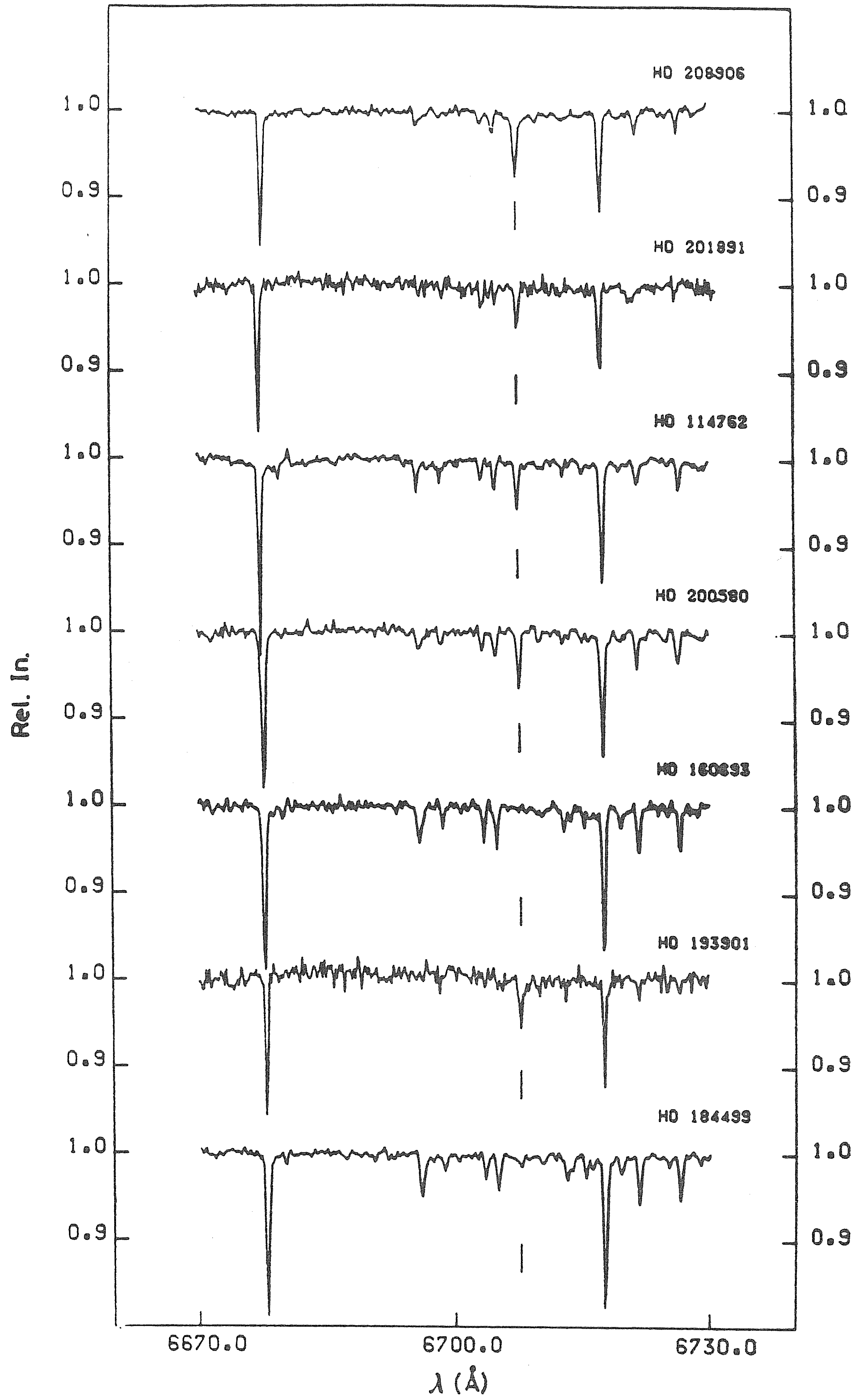


Fig 2.3.a New observations of lithium in population II stars: spectra of "highly metal-deficient" dwarfs (-1.4<[Fe/H]<-0.6).

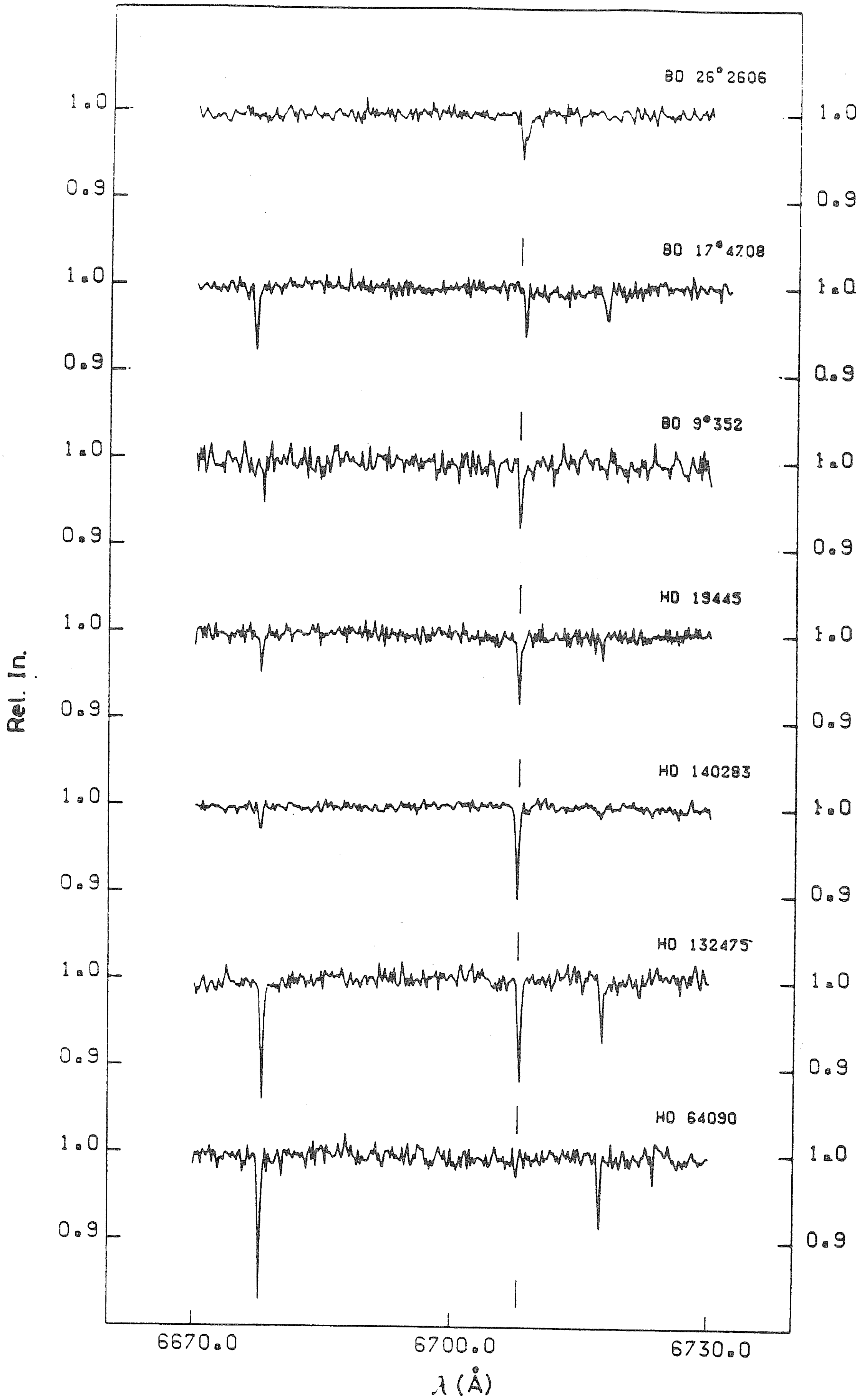


Fig 2.3.b New observations of lithium in population II stars: spectra of "extremely metal-deficient" dwarfs ([Fe/H]<-1.4).

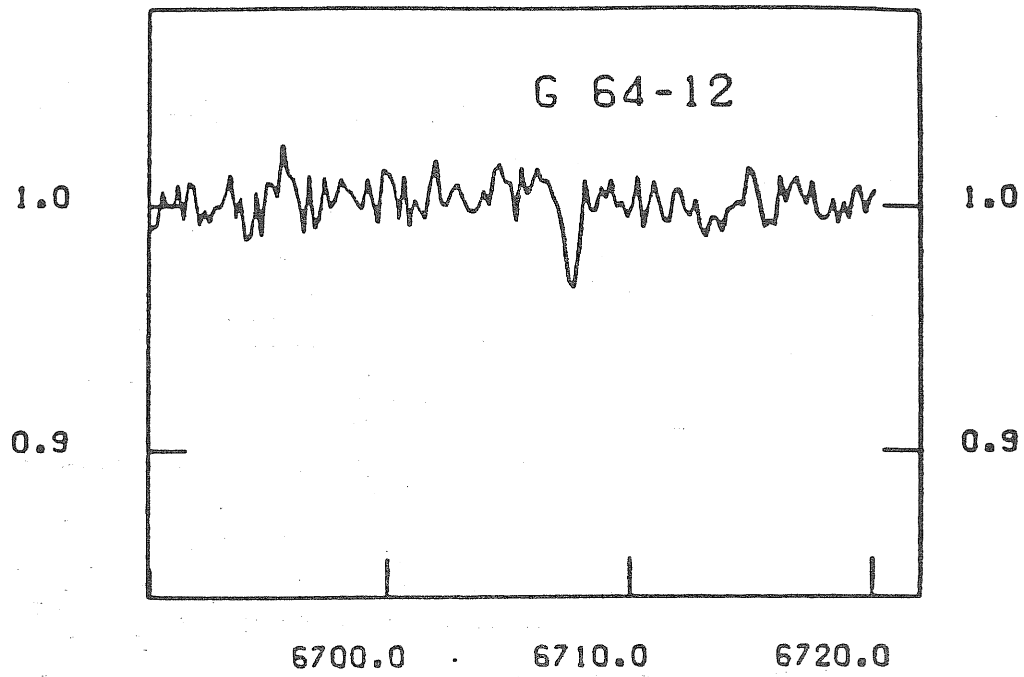


Fig 2.4 The Li line at 6708 A in G64-12.

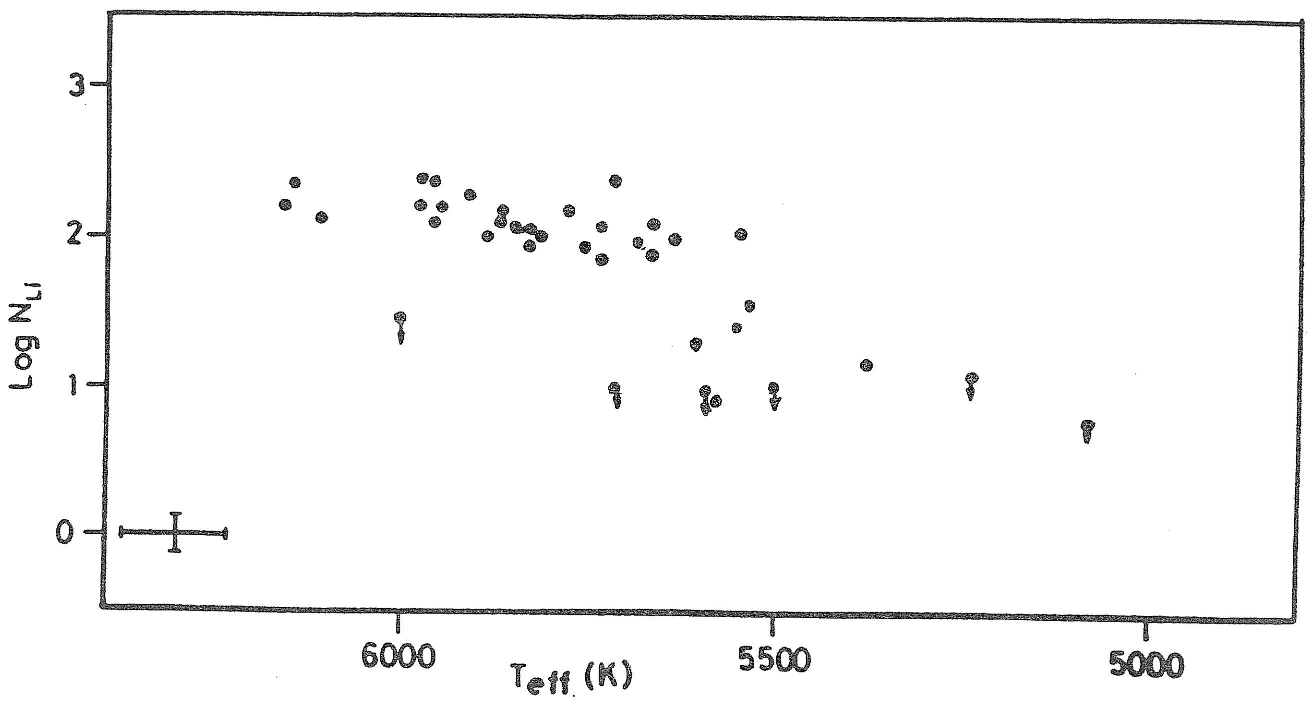


Fig 2.5 Lithium abundances against Teff for 37 metal deficient dwarfs.

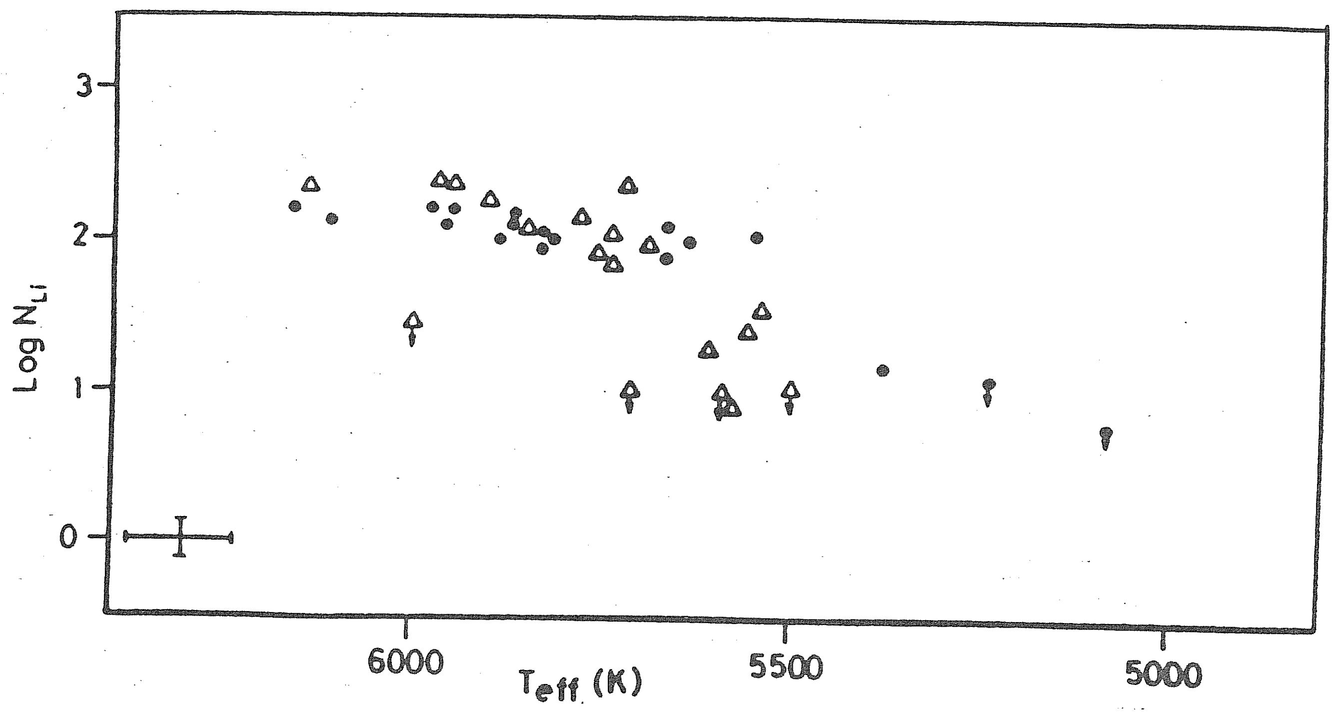
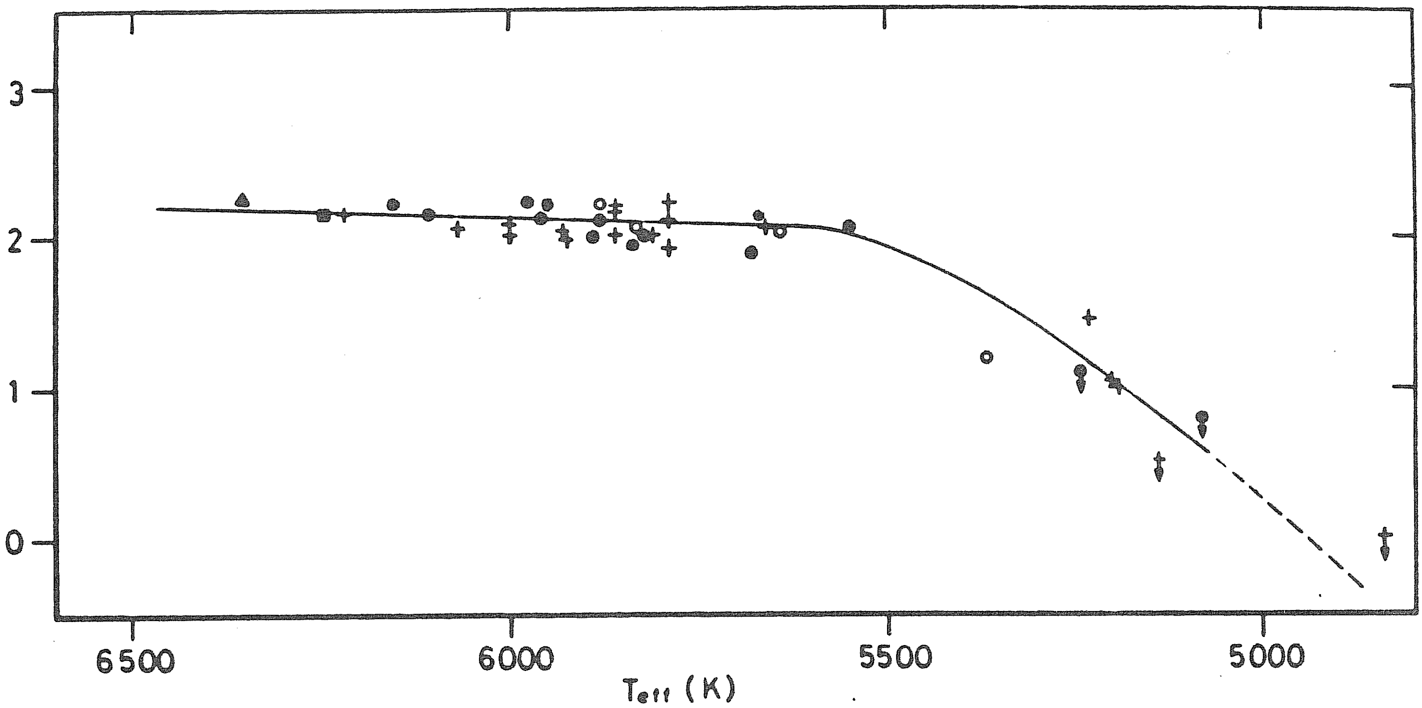


Fig 2.6 As Fig 2.5. Solid symbols are for "EMD" stars ([Fe/H]<-1.4), open triangles are for "HMD" stars (-1.4<[Fe/H]<-0.6).


3
2
1
0
6500
6000
5500
5000
Teff (K)

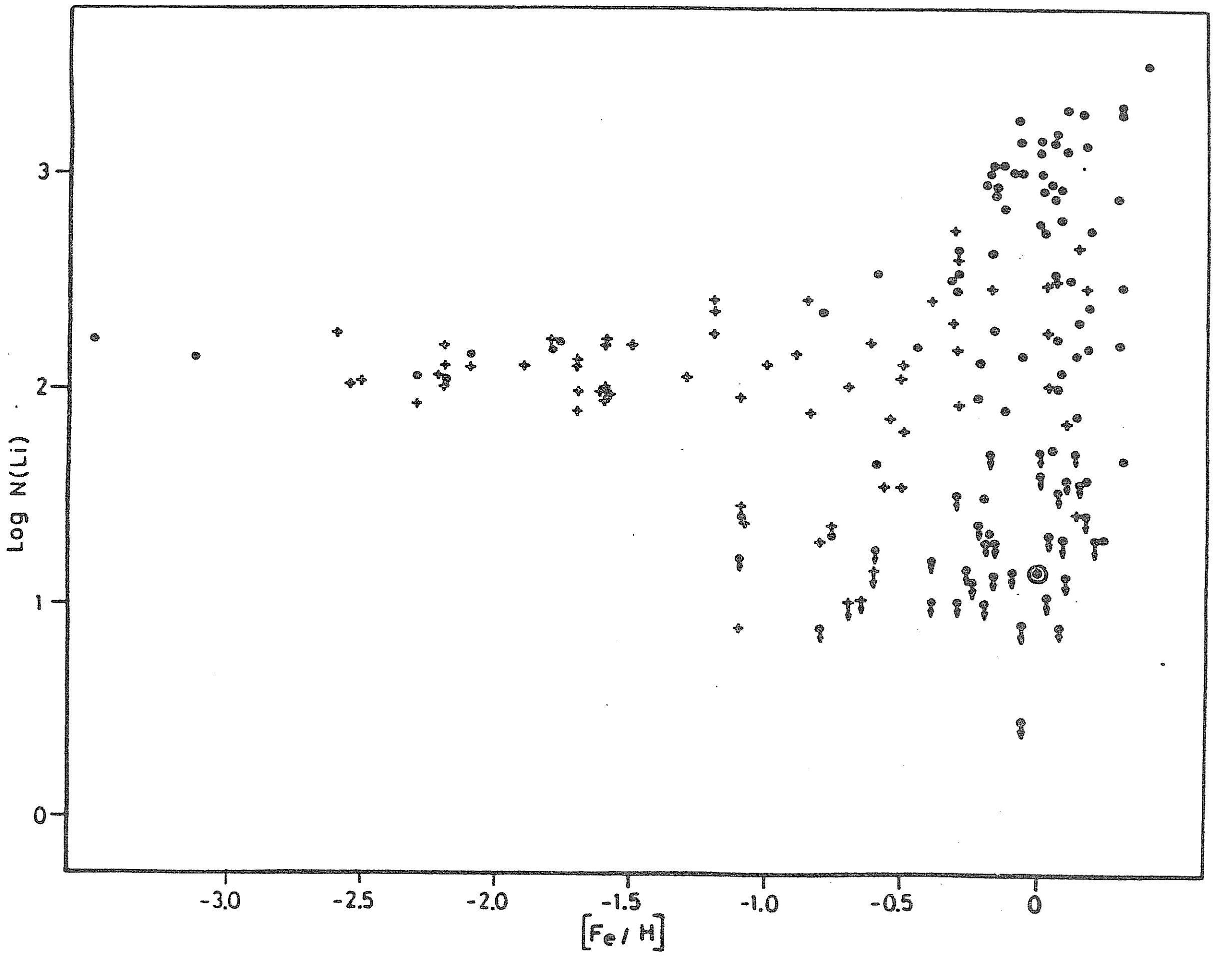


Fig 2.7 Compilation of all lithium abundances against metallicity for stars with Teff>5500 K. Typical error bars for LogN(Li) and [Fe/H] are 0.1-0.2 dex. Solid symbols are for Teff>6000 K and crosses for 5500<Teff<6000. Sources of data: Spite et al (1982, 1984, 1986) Boesgaard and Tripicco 1986a,b), Rebolo et al (1987), this work.

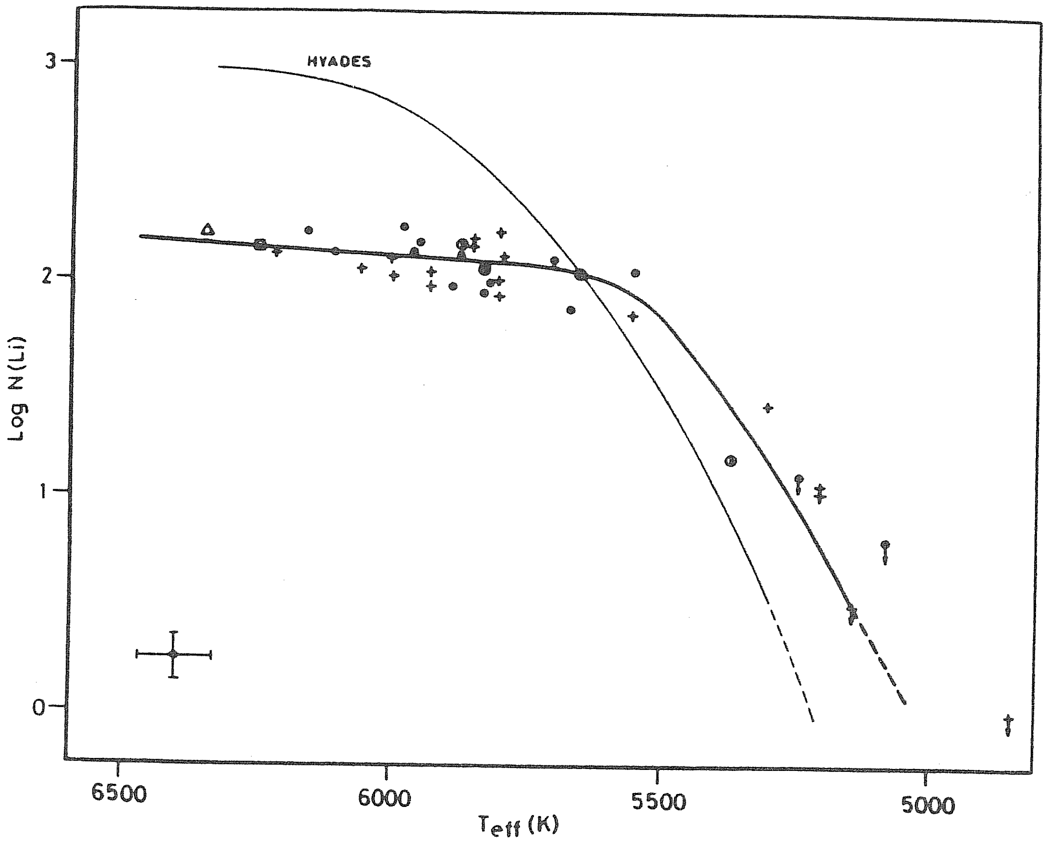


Fig 2.8 Lithium abundances against Teff for EMD stars ([Fe/H]<-1.4). Solid symbols are from the present work; crosses for Spite et al (1982, 1984, 1986); triangles for Rebolo et al (1987); open squares from Boesgaard (1985). Also shown is the curve for the Hyades using data from Cayrel et al (1984) and Duncan and Jones (1983)

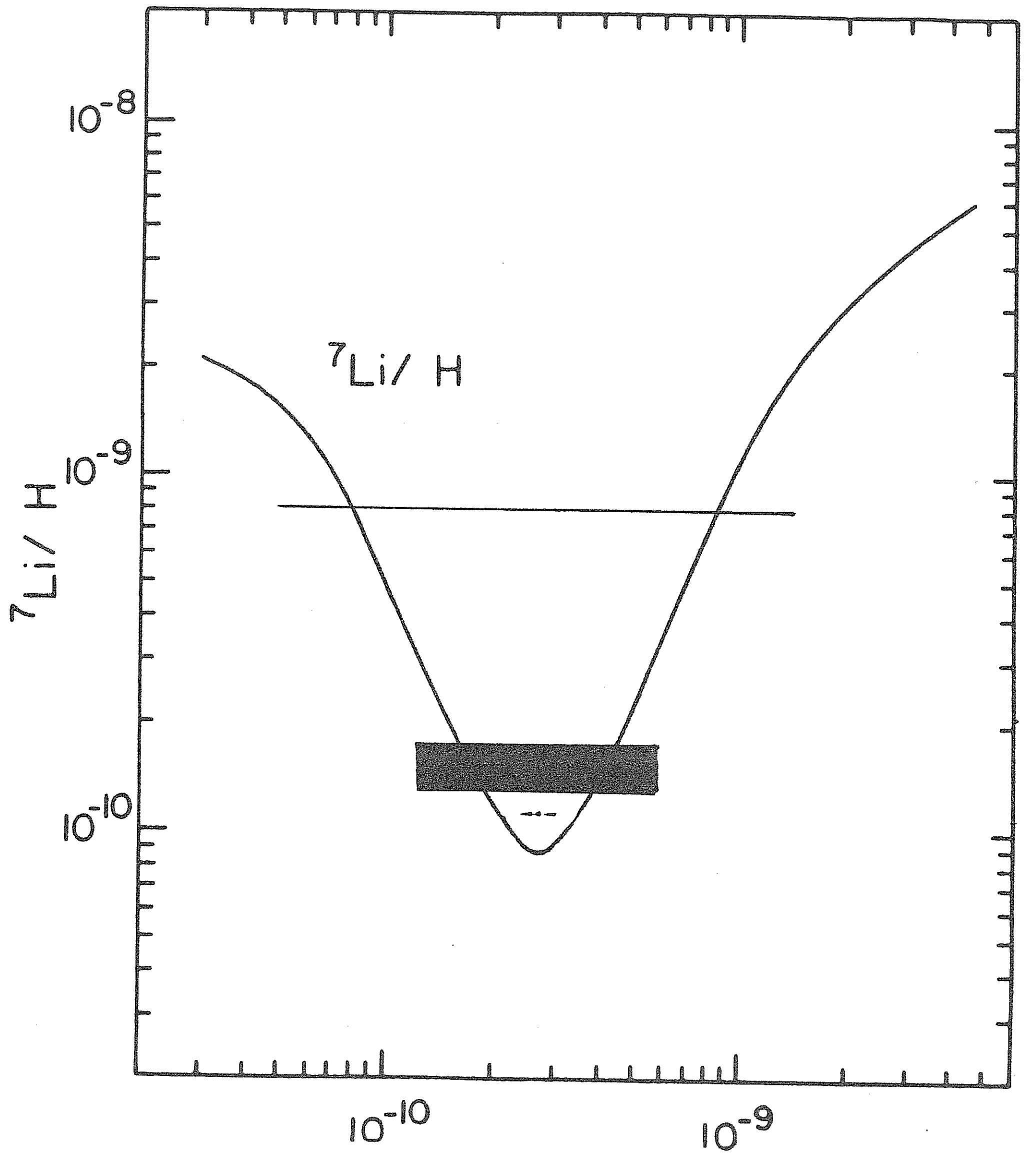


Fig 2.9 Theoretical curve for primordial lithium production as a function of the baryon-to-photon from Kajino et al (1987) showing the restrictions on eta imposed by our estimate lower limit for primordial Li.

3. OBSERVATIONS OF BERYLLIUM IN POPULATION II STARS

3.1 OBSERVATIONS OF BERYLLIUM

^{9}Be is the only long-lived nuclide of Beryllium. ^{7}Be and ^{10}Be are instable isotopes with disintegration periods of 53.6 days and 2.7×10^{6} years respectively. Thus, unless these latter isotopes are recently formed, ^{9}Be is the only isotope that can be observed in the stellar atmosphere.

The determination of the abundance of beryllium relies entirely on the observation and interpretation of the resonance doublet at 3130 A of Be II, $^{2}S-^{2}P^{o}$. The other possible triplet of BeI 3321.2 A $^{3}P-^{3}S$ cannot be detected even in the solar spectra.

The abundance of Be was first determined in the sun by Greenstein and Tandberg-Hanssen (1954). Subsequently the observations were extended to normal A,F, and G stars (for a review of these early works we refer to Wallerstain and Conti (1969). So far the most extensive and omogeneous set of observations is that of Boesgaard (1976) who in a sample of 27 stars found $\langle Be/H \rangle = 1.31(\pm 0.36) \times 10^{-11}$. In six F and G main sequence stars belonging to the Hyades Boesgaard et al (1977) found $\langle Be/H \rangle = 1 \times 10^{-11}$ consistent with the other field stars of the same spectral type. More recently Be has been studied in

Sirius and Vega by Griffin (1985).

The solar abundance has been recomputed using more accurate data by Ross and Aller (1974) and with the aid of center-to-limb observations by Chimielewski et al (1975), who found $Be/H=1.2x10^{-11}$ and $Be/H=1.4(+/-0.6)x10^{-11}$ respectively. In meteorites the Be/Si ratio is between 5 and $10x10^{-7}$ (Buseck 1971) corresponding to a Be/H of about $2x10^{-11}$. A search for Be in chemically peculiar stars showing large Li abundances has been undertaken by Gerbaldi Faraggiana and Molaro (1986). A list of ^{9}Be abundances in the solar neighbourhood is given in Table 3.1.

3.2 Beryllium observations in the Population II stars

Relatively less effort has gone into observing stars older than the sun for beryllium. Reeves and Meyer (1978) have estimated ages greater than the sun for certain field stars and, even in these, found abundances close to the solar value. These data taken as a whole show that the ^{9}Be abundance has remained unaltered during the 10 billion years covered by the that range of observations. Abundance of beryllium in the population II stars has been derived for the first time by Molaro and Beckman (1984) and Molaro Beckman and Castelli (1984). In the following we descrive these results together with more recent observations in other stars.

Knowledge of abundance of ^{9}Be in stars found early in the galaxy lifetime gives important information on the origin of those elements understood to be produced by galactic cosmic ray spallation processes, burst of star formation in the early stages of evolution of the galaxy, depletion processes in the sub-photospheric layers of low metallicity stars and, by comparison with ^{7}Li abundances, information on the fraction of primordially produced lithium.

3.3 Beryllium observations with IUE data

The spectral region containing the BeII lines is covered by the long wavelength (LWR) spectrograph of the IUE satellite. From the IUE data bank at Villafranca, Spain (VILSPA) we took the LWR images No. 7182 of HD 7632, and LWR 5345 of HD 140283. The spectra were taken in the high resolution mode ($\Delta\lambda/\lambda$=0.2 A), with the large entrance aperture to the spectrograph. In the LWR 7182 there is a reseaux mark close to the 3130.42 line. Fortunately the weaker line at 3131.065 A is not affected by the reseaux mark.

The BeII resonance lines are in a region where a great density of lines is found and where the continuum opacities are not fully understood. All Be observations face with the problems of the "blending" of lines and of the missing ultraviolet opacities. The stronger of the resonance doublet at 3130.420 is blended with VII at 3130.261 and with the TiII at 3130.791. It is common practice to use the fainter less blended at 3131.065 and to account for blending by means of the use of a synthetic spectrum. A good photometric accuracy is required since the problem of blends is increased in any spectrum with insufficient signal to noise ratio. The importance of obtaining spectra with good resolution is clear from the fact that a limiting resolution of 0.1 A is needed in order to eliminate blend contamination of the 3131.065 A line.

As the IUE spectral resolution falls somewhat short of the

desired value, it is important to optimize this when extracting the spectrum from the raw data. We used a suite of computer codes ("IUEARM") to sharpen the LWR spectra and to estimate the rms noise level. This technique takes spectral data from the second file of the IUE standard tape, and instrumental data from the third file, and begins by performing a two-dimensional Fourier transform of the whole IUE Echelle image. High frequency noise is removed via a two dimensional gaussian filter, and the data deconvolved using a gaussian-lorentzian fit to the IUE instrumental profile. After removal of the measured background, the relevant order is scanned with a two pixels pseudo-slit, which is constrained numerically to follow the peak intensity of the cross cut. This small slit reduces the probability of encountering image flaws, and yelds a limited but useful improvement in the spectral resolution compared to IUESIPS (the standard VILSPA routine).
The CrII line at 3132.036 A was used to establish the zero point of the wavelength scale.

3.4 Be observations at La Palma

The observations were carried out with the 2.5 m Isaac Newton Telescope of the observatorio del Roque de los Muchachos (La Palma) with the IDS (Intermediate Dispersion Spectrograph) and the 500 mm spectrograph camera on the nights 13-15 August 1984, and 3 October 1985.
The H 2400B holographic grating, optimized for the blue, gave a dispersion of 8 A/mm in the wavelength range used. The detector was an Image Photon Counting System (IPCS), Boksemberg (1972).

In the configuration employed, a single pixel corresponded to 0.12 A. The size of the IPCS photocathode took in a total range of 200 A around the BeII doublet at this wavelength.

Flat field exposures were taken at the beginning and end of each night's run. For this istrument there is no read-out noise, and for the present spectra photon noise strongly predominated over the dark counts.

Higher signal to noise ratios were not easy to obtain in reasonable exposure times, i.e. within a few hours per object, given the system limit of 0.5 photons/pixelxsec required to avoid non-linearities due to photon-photon coincidences.

With each stellar spectrum an exposure of a CuNe arc was obtained for the purpose of wavelength calibration. The spectra were calibrated in wavelength by comparing the absorption in the observed spectra with the known wavelengths of the clearly recognizable features due to CrII at wavelength 3132.055 and VII at wavelength 3133.335.

The log of the observations is shown in Table 3.2. In this table we list the stars selected, their magnitudes, the observation epochs, exposure times and signal to noise ratios achieved, as well as important kinematic parameters.

3.4.1. Analysis of the data

Since most aspects of the analysis of the data to obtain the Beryllium abundance are in common to both the different sets of data we treat them together.

The stars are the brightest halo dwarfs of the sample used for lithium observations and the basic atmospheric parameters have

been already discussed in the chapter of ^7Li observations.
The Teff value, for all the stars except HD 189558, come from b-y, V-K, and R-I indices measured and calibrated by Carney (1983) and log g from our own interpolation of the indices b-y and cl, also from Carney (1983). For HD 189558 model parameters were adopted from Spite et al. (1984).
For HD 194598 and HD 189558 the metallicity was taken from the literature, while for the other stars in the sample we used a set of clean unblended Fe lines in the spectral range near to the the ^7Li doublet at 6707 A (Beckman et al 1986).
The range of Fe abundances in the stars was $-2.2<[Fe/H]<-1.0$ for the logaritmic ratio respect to the solar value. Differently from lithium the Be abundance is not very sensitive to the effective temperature. Values for Teff, Log g and [Fe/H] are listed in Table 3.3.

Both the spectra of IUE and La Palma were analyzed using a spectral synthesis programme as described in the sections dealing with lithium determinations. In computing the abundance of an individual element by this synthesis method we use a global figure for the metallicity to obtain the continuum opacity required by the model, and than "fine tune" the abundance of the element so that its observed lines in our spectral range are matched by the synthetic spectrum.
A micorturbolence value of 1.5 Km/sec was employed in the synthetic programme.

Individual synthetic spectra were convolved with gaussians to represent the combined effects of stellar rotation and instrumental broadening. For the data obtained with the IDS+IPCS the range of FWHM's for these stars was 0.28 A 0.30 A, values were derived by matching the least blended synthesized lines in the range to the obseved lines. Variations within this range produced, in any case, negligible variations in the derived Be abundances.

The region around 3130 A contains many absorption lines, which have been detected and identified in high resolution spectra of the sun (Moore et al. 1966, Ross and Aller, 1974). In our synthesis we used a basic set of lines from Kurucz and Peytremann (1975), the line list used is given in Table 3.4. Of the two BeII lines that at 3130.420 A is the stronger (log gf=-0.168) but is the less easy to use for abundance analysis given the contamination by the VII line at 3130.261A, and by two further absorptions even closer in wavelength: at 3130.567 and 3130.631 A (Moore et al 1966). The latter have been examined in the sun by Ross and Aller (1974) who suggested the presence of one line due to FeII and two OH lines. We have not included these two lines in the synthesized spectra presented here because of the difficulty of assigning reliable strengths to them. However we have, in a series of trials, verified that the inclusion of these lines, even with solar equivalent widths, would not affect the region of the weaker of the two lines in the BeII doublet. This line (log gf=-0.468) is better placed for a reliable analysis. Even here, however, there is a neighbouring contaminant: the Ti II line at 3130.791 A. We obtained an independent abundance of Ti before examining the Be abundance using the unblended TiII line at 3224.233 A that falls within our spectral range. Using a value of log gf=-0.17 (Roberts et al. 1973) we found the Ti abundance listed in Table 3. An error of 0.4 dex in the Ti abundance was shown to have a negligible effect on the derived Be abundance. The abundances of the other metals in the range, less critical for Be determinations, were taken into account by scaling in direct proportions to the Fe abundances.

These values were used in the final synthesis, from which the Be abundances were found by varying the value of Be to give best fits to the observed spectra. The possible presence of OH lines can well account for the detailed discrepancies between the synthesized and observed spectra at these points, but they do not affect our estimates of Be.

3.4.2. Beryllium abundances from IUE data

Examples of synthesized spectra for HD 76932 are shown in Figs. 3.1a with a solar abundance of 1.3×10^{-11} for Be/H, and 3.1b with a Be/H abundance 10 times lower. The synthetic spectrum at 3131.065 with solar Be/H is much stronger than any feature at the same wavelength in the observed spectrum. Taking into account the noise levels within the IUE spectrum we can set a two sigma upper limit to the ^{9}Be abundance of Be/H$<$ 3×10^{-12}. But the uncertainty in the choice of continuum level is particularly difficult to estimate. We are aware of two possible sources of opacity at 3131 which could marginally affect our conclusion. In the solar spectrum there is a weak violet asymmetry in the observed Be of unknown origin (Chimielewski et al 1975). In addition there may be an additional source of continuous opacity as pointed out by Chimielewski et al (1975) from solar-to-limb observations. In either case, and for additional opacity due to any possible blending also, the effect would only be to reduce the above upper limit

In Fig. 3.2 it is shown the comparison of HD 140283 spectrum with theoretical model with solar Be abundance. It is possible to see that the computed Be line is much stronger than any feature at 3131.065 in the observed spectrum. The best fit to the observed spectrum is given by $Be/H=0.1(Be/H)_{\odot}$ i.e. $1.3x10^{-12}$. An upper limit at $3x10^{-12}$ can be placed considering the uncertainties of IUE data. Additional confirmation of the validity of the derived upper limit comes also from the 3130.4 A that for low Be abundance is in better agreement with the spectrum.

3.4.3. Beryllium abundances from IPCS data

In Fig 3.3 we show the observed spectra of HD 201891, which has metallicity [Fe/H]=-1.0, in the range 3129-3133 A together with synthesized spectra.
These spectra were computed for the solar Be abundance, i.e. $Be/H=1.2x10^{-11}$, for absence of Be and for the best fit Be abundance, which is $Be/H=2.5x10^{-12}$.
In figure 3.3b we show the effect of varying the Be abundance by a factor 2 either side of the best fit (i.e. by +/-0.3 dex). It can be clearly seen that the synthesized spectra are worse fits to the observed spectrum in both of these cases.
Similar conclusions with similar bracketing of the Be abundances, can be drawn for the stars BD 23 3912 and HD 189558.

In Fig. 3.4 we show synthetic spectra matched to the observed spectrum of HD 19445, also in the range 3129-3133 A.

For this star, which has metallicity [Fe/H]=-2.2 according to our own analysis, the matching synthetic spectra shown are for the cases of absence of Be, and abundances Be/H=1×10^{-12} and Be/H=2×10^{-12}. We have chosen the last value as the upper limit to the observed abundance. It could be felt that 1×10^{-12} is a better fit, which would imply a marginal detection.

Upper limits were also set for HD 219617 and HD 194598.

No previous detections of Be in stars of such low metallicity have been reported in the literature. Those results are in agreement with the upper limit derived using IUE data.

As a check on our analysis technique, we obtained and analysed the BeII region in the star 17 Cyg which has a metallicity close to solar. From our spectrum (S/N=27) a Be/H=$7(+/-4)\times10^{-12}$ was derived using model atmosphere parameters taken from Boesgaard (1976). This result is in agreement with the Boesgaard's (1976) own estimation of Be/H=1×10^{-11} within our error limit.

The final results for the Be abundances and upper limits are shown in Table 3.3. In stars with metallicities of order of [Fe/H]=-1, Be is detected, with abundance Be/H=2×10^{-12}, while for stars with metallicities [Fe/H]<-1.5, we set upper limits in the range 1-2×10^{-11}.

3.4.3. Errors

The results must be considered in the light of the observational and inferential errors inherent in the present work. The use of a Kurucz model with [Fe/H]=-1.0 or [Fe/H]=-2.0

for continuum opacities did not lead to significant change in our Be abundance estimates, i.e. the change in abundance due to the change in continuum opacity was small compared with observational uncertainties. Boesgaard (1976) has shown that changing Teff between 5700 K and 6600 K produced very small variations in the Be equivalent width.

The S/N ratios in the spectra lead to uncertainties which are somewhat less than 0.3 dex in the Be abundance. Uncertainties of +/-1 Km/sec in the microturbulence lead to negligible errors in Be/H.

Combining quadratically independent sources of error we have characteristic uncertainty of 0.4 dex in the resulting Be abundances and upper limits. Uncertainties for individual objects are shown in table 3.3.

3.5 Evolutionary Abundance Curve for Beryllium

To define the value of the Be abundance at the time of formation of the star we have to consider the possibility of subsequent depletion may have occurred. Nuclear processes in stellar interiors destroy ^{9}Be at temperatures higher than 3.5 10^{6} K and depletion starts where mixing is significant. There is observational evidence that depletion is occurring in stars cooler than K5 (Boesgaard 1976) in agreement with the theoretical expectation (Bodenheimer, 1966). The stars under study have all temperatures between 5500 and 6000 K and depletion is not expected. The stars are all far from the "danger zone" temperature Teff>6500 K where 30% of stars do show depletion (Boesgaard 1976). Moreover our stars have measured lithium, undepleted or very little depleted, and since lithium is more fragile than beryllium we can infer that Be in these stars should be undepleted.

We have made Be determinations in a lower metallicity range than previously reported, and can now draw conclusions about Be virtually in the whole range of metallicities. In Figure 3.3 we have plotted Be abundances [Be/H] against metallicity [Fe/H]. The graph contains a point summarizing Be abundances for the Hyades, a point for the solar abundance and a points for stars of metallicities down to -0.5, as well as including the stars in the present programme. It seems from these observations that Be has never had an higher abundance than the solar value at any time in the past history of the galaxy. The most relevant feature of Figure 3.3. is the contrast between stars of metallicity -0.5 which have Be abundances with essentially solar values, and stars of metallicity -1 which we have shown to have much lower Be abundances. Between these two values of metallicity there was a rapid rise in the Be abundance of the Galaxy.

There are a number of theoretical models which address themselves to predict the present observed ^{9}Be abundance. Although they all agree in assuming that ^{9}Be is built up via spallation processes, they differ in their predictions about the rate of this build-up, because they assume different star formation rates, especially close to the epoch of formation of the galaxy. All the models give satisfactory fits to the present beryllium abundance but they predict widely different Be abundances in those stars formed very early in the lifetime of the galaxy (within the first 10^{9} years). Thus measurements of the ^{9}Be abundance in objects in the age range within one gigayear of the initial stellar component of the galaxy will give a datum of major significance in testing detailed models of the chemical evolution of the galaxy as a whole.

To summarize, one set of models includes a strong burst of star formation back to the epoch of formation of the galaxy, which would have led to high cosmic ray fluxes and hence high ^9Be in the oldest stars. The other set of models include a steady build-up of ^9Be between the galaxy origin and $5x10^9$ years of the galaxy life followed by a more or less steady equilibrium between production and destruction. These models predict low ^9Be in stars closer to the epoch of formation of the galaxy.

Our previous results are consistent with the second picture.

The significant of our observations is that it appears to rule out one of the two set of families of models which set to account for the observed abundances of ^9Be in stellar atmosphere. Models which predict high early abundances of Be, such as those with an early burst of star formation (see Audouze and Tinsley, 1974) are ruled out.

On the other hand a number of models which do not make this assumption and which include (or not) infall of unprocessed matter (Truran and Cameron 1971, Reeves and Meyer 1978) can be tested by the data in figure 3.3. In the figure is also shown a theoretical model recently worked out by Abia and Canal (1987). In the figure we also show how Be varies with time in the model. We can infer that all of our stars in the present sample were formed within only $5x10^8$ years of the origin of the model.

3.6 Deduced abundance evolutionary curves for lithium and boron

It is known that spallation can produce not only Be but also ^{6}Li, ^{7}li, ^{10}B and ^{11}B. Our Be observations can be used to predict the abundances of other light elements produced by spallation processes in the ISM. Of these only ^{7}Li is produced in measurable quantities by processes other than spallation but it is implausible that a significant abundance could have been produced either in red giants or in novae at such an early epoch because of the larger time-scales involved. Thus the lithium observed in these stars can only come either from spallation or from pre-galactic processes. That ^{7}Li could have been produced by cosmic ray spallation in that early epoch as it has been shown by Audouze and Tinsley (1974).

The importance of Be observations in Pop II stars is to rule out, apparently, "non Big Bang" sources for ^{7}Li in the galaxy prior to the formation of population II.

In order to estimate the spallogenic abundances of all the nuclides produced by spallation processes we have taken for stars with metallicities [Fe/H]=-1 a mean value of 1.8×10^{-12} for Be/H and adopted the theoretical isotopic ratios calculated by Walker et al (1985). The results are $^{6}Li/H=8.3 \times 10^{-12}$, $^{7}Li/H=1.2 \times 10^{-11}$, $^{10}B/H=8.5 \times 10^{-12}$, and $^{11}B/H=2.2 \times 10^{-11}$.

These predictions can be used to constrain the fraction of observed Li in metal deficient stars which could be spallogenic and the fraction of the 6708 A ^{7}Li doublet used for the abundance determination of this element which could be due to ^{6}Li. Assuming as a typical value for ^{7}Li in the halo dwarfs $^{7}Li/H=1.3 \times 10^{-10}$ we have a $^{7}Li/^{6}Li$ ratio of aproximately 15. This is consistent with the limit of 10 derived observationally in two old unevolved dwarfs by Maurice et al. (1984), although slightly more restrictive.

As ^{6}Li is more fragile than ^{7}Li if some limited depletion is occurred an even higher ^{7}Li/^{6}Li ratio in the atmospheres of these stars would be expected. Hence the largest effect that contamination by ^{6}Li could have on the presumed abundance of ^{7}LI is to reduce it by 0.03 dex.

The abundance of spallogenic ^{7}Li indicates that it is about 5% to 10% of the total ^{7}Li, the exact value depending on the particular star. This contribution would reduce the primordial ^{7}LI abundance by the same amount.

If we confine our attention to stars with [Fe/H]<-1.5 a lower reduction is expected.

The present ^{9}Be observations imply that non-primordial contributions to the 6708 A line due to spallogenic ^{7}Li or spallogenic ^{6}Li would not be higher than 0.1 dex, which is comparable to the uncertainties in the measurements. This removes an important uncertainty in the ^{7}Li abundances themselves, allowing an improved chek on the universal baryon-to-photon ratio.

Source	$^{9}Be/H$	Reference
Meteorites	2×10^{-11}	Busek (1971)
	$3.6(\pm1.3)\times 10^{-11}$	Reeves & Meyer (1978)
Sun	1.2×10^{-11}	Ross & Aller (1974)
	$1.4(\pm0.6)\times 10^{-11}$	Chmielewski et al (1975)
Population I (stars F and G)	$1.3(\pm0.36)\times 10^{-11}$	Boesgaard (1976)
Hyades	$1.0(\pm0.1)\times 10^{-11}$	Boesgaard et al. (1977)
Sirius	$<2.5\times10^{-12}$	Griffin and Griffin (1985)
Vega	$<4\times10^{-12}$	" " " " "
Interstellar Medium	$<8.4\times10^{-12}$	Boesgaard (1985)
Old Population I		
α Cen A	2.5×10^{-11}	Dravins & Hultqvist (1977)
μ Her	1.2×10^{-11}	Boesgaard & Chesley (1976)
ϵ Eri	0.22×10^{-11}	Boesgaard & Chesley (1976)

Table 3.1 Beryllium abundances in the solar neighbourhood.

Star	V	Date	Exp. (sec.)	S/N	v_{rad} (km/s)	w (km/s)	e	Ref
HD 19445	8.05	3-10-85	6000	37	-143	-57	0.615	E
HD 189558	7.74	3-10-85	5300	19	-15	47	0.530	E
HD 194598	8.40	15-08-84	4700	22	-248	-18	0.995	E
HD 201891	7.30	15-08-84	4000	33	-45	-61	0.515	E
HD 219617	8.17	15-08-84	4330	17	10	-44	0.985	E
BD 23°3912	8.90	3-10-85	4780	16	-115	59	0.400	B

Notes: v_{rad} is radial velocity of star, w is the third component of the velocity vector and e the eccentricity of the galactic orbit. Sources for kinematics: E Eggen (1979), B Bond (1970).

Table 3.2 Log of the observations

HD/BD	Teff	log g	[Fe/H]	Ref[a]	Ti/H	Li/H	Be/H
19445	5830	4.0	-2.2	1	6.3×10^{-10}	1.20×10^{-10}	$<2.0 \times 10^{-12}$
189558	5660	4.0	-1.3	2	2.0×10^{-9}	1.10×10^{-10}	$1.0(2.5) \times 10^{-12}$ *
194598	5860	4.0	-1.6	2	4.0×10^{-9}	1.00×10^{-10}	$<2.0 \times 10^{-12}$
201891	5870	4.5	-1.0	1	4.6×10^{-9}	1.20×10^{-10}	$2.5(\pm 2.5) \times 10^{-12}$
219617	5870	4.5	-1.5	1	3.9×10^{-9}	1.58×10^{-10}	$<2.5 \times 10^{-12}$
23°3912	5700	4.0	-1.3	1	3.2×10^{-9}	2.50×10^{-10}	$2.0(2.5) \times 10^{-12}$ *

a Values for [Fe/H] and Li/H taken from: 1 Beckman et al. (1987). 2 Spite et al. (1984). * The number 2.5 in parenthesis indicates uncertainty of a factor 2.5 in either direction. The upper limits are considered to be established within ($\pm 1\sigma$).

Table 3.3 Basic stellar parameters and Be/H abundances

Line	(Å)	X_L (eV)	log(gf)
Ni I	3129.299	0.280	−3.084
Fe I	.335	1.480	−2.610
Nb II	.640	2.310	−0.400
Zr II	.760	0.030	−0.430
Y II	.930	3.390	0.640
V II	3130.261	0.350	−0.277
Ce II	.330	0.520	−0.200
Be II	.420	0.000	−0.168
Cr II	.544	5.330	−0.485
Nb II	.790	0.430	0.380
Ti II	.791	0.010	−1.074
Cd II	.810	1.150	−0.160
Ce II	.870	0.000	−0.630
Be II	3131.065	0.000	−0.468
Os I	.120	1.830	0.530
Cr I	.212	3.110	−0.001
V I	.218	1.220	−0.423
Tm II	.260	0.000	−0.170
Fe II	.335	3.810	−3.553
Ni I	.525	3.190	−2.164
Cr II	.538	4.180	−1.283
Cr II	.539	4.170	−1.545
Ni I	.702	3.310	−1.272
Fe II	.715	4.080	−1.855
Hf I	.810	1.300	0.420
Cr II	3132.036	2.480	0.454
Zr I	.070	0.540	0.020
CO I	.212	0.100	−2.077
Fe I	.514	3.210	−0.924
V II	.587	2.900	−1.203
Ce II	.590	0.290	−0.570
Mo I	.590	0.000	0.160
V II	.785	2.510	−1.652
Mn I	.788	4.270	−0.215
Cr I	.821	3.120	0.142
Ni II	.864	2.860	−3.783
Ru I	.880	1.310	−0.360
Fe II	3133.047	3.890	−1.736

ble 3.4 Line list used in the synthetic spectrum for the gion near 3131 A.

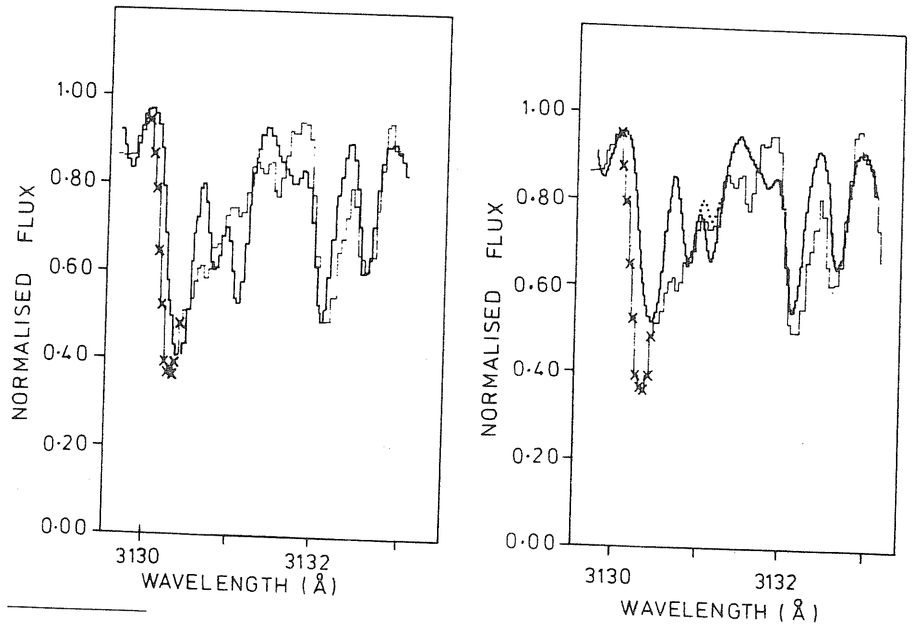


Fig 3.1 Comparison of observed spectrum of HD 76932 in the region of 3131 A with the output of the theoretical model. A solar Be abundance $^{9}Be=1.3x10^{-11}$ (left) and with a $^{9}Be=3x10^{-12}$ (right). The dots display the 3131.065 A line for $^{9}Be=1.3^{-12}$.

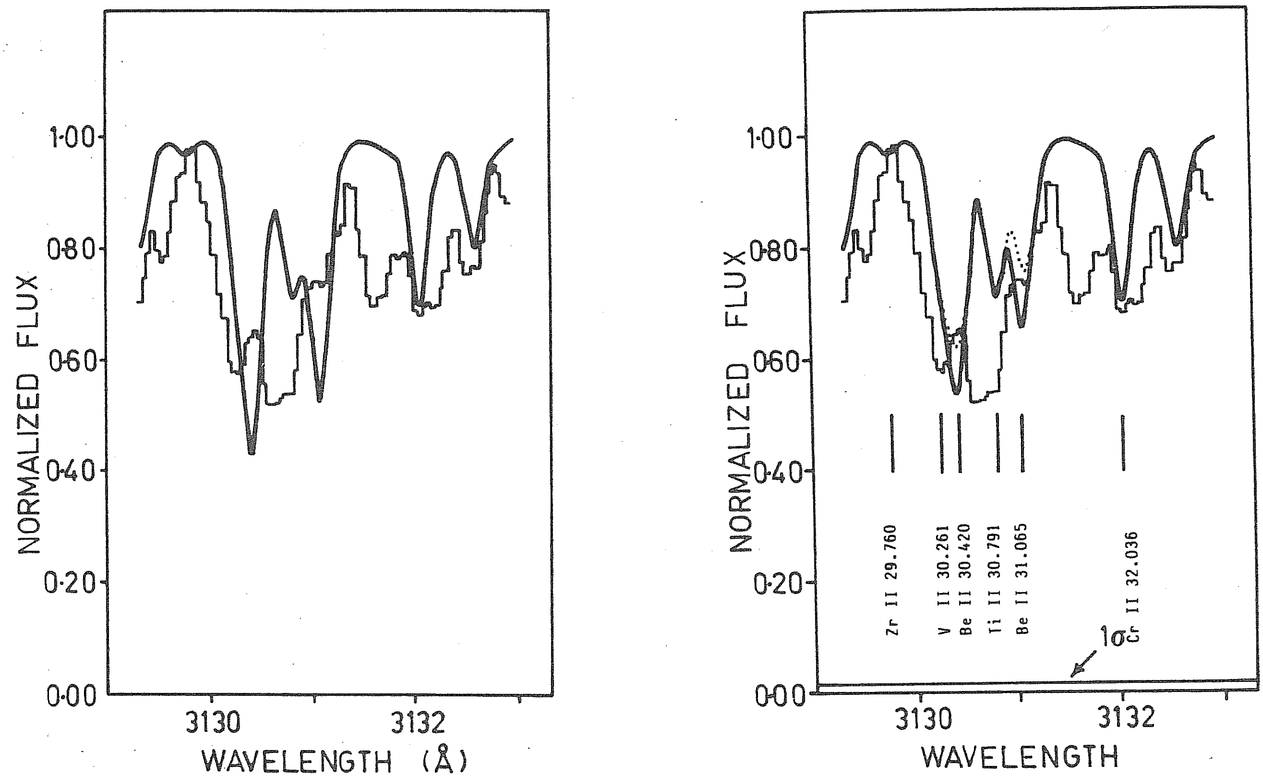


Fig 3.2 On the left it is shown the comparison of an IUE spectrum of HD 140283 with a theoretical model with solar abundances for ^{Be}. On the right the models are for ^{9}Be=3x10^{-12} and for ^{9}Be=1.3x10^{-12} (the dots).

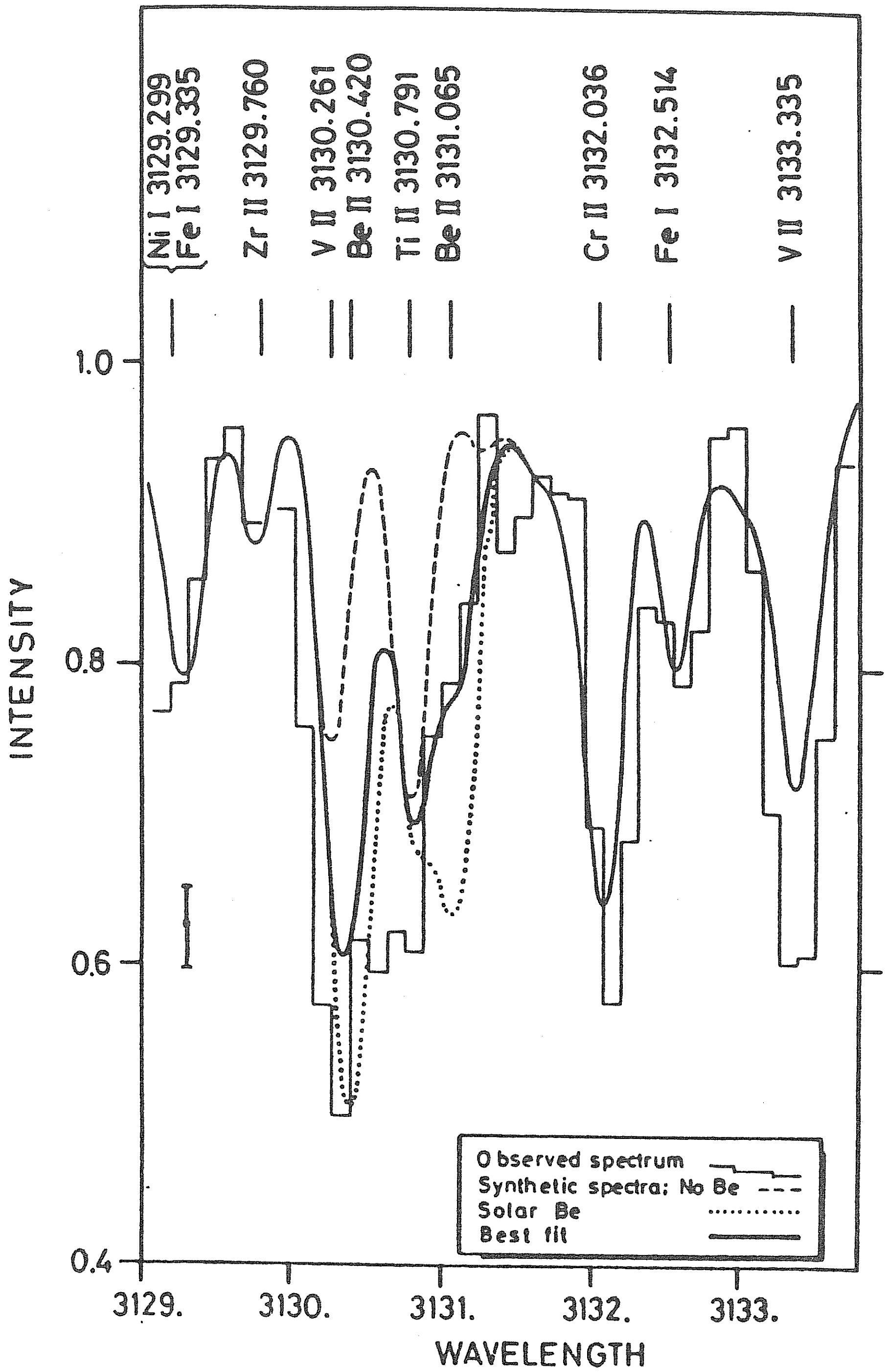


Fig 3.3a Observed spectrum of HD 201891 ([Fe/H]=-1.0) in the range containing the BeII doublet together with the synthesized spectra for three cases: no Be, ii) solar Be, iii) Best fit ($Be/H=2.5x10^{-12}$). A 1 sigma error bar is plotted.

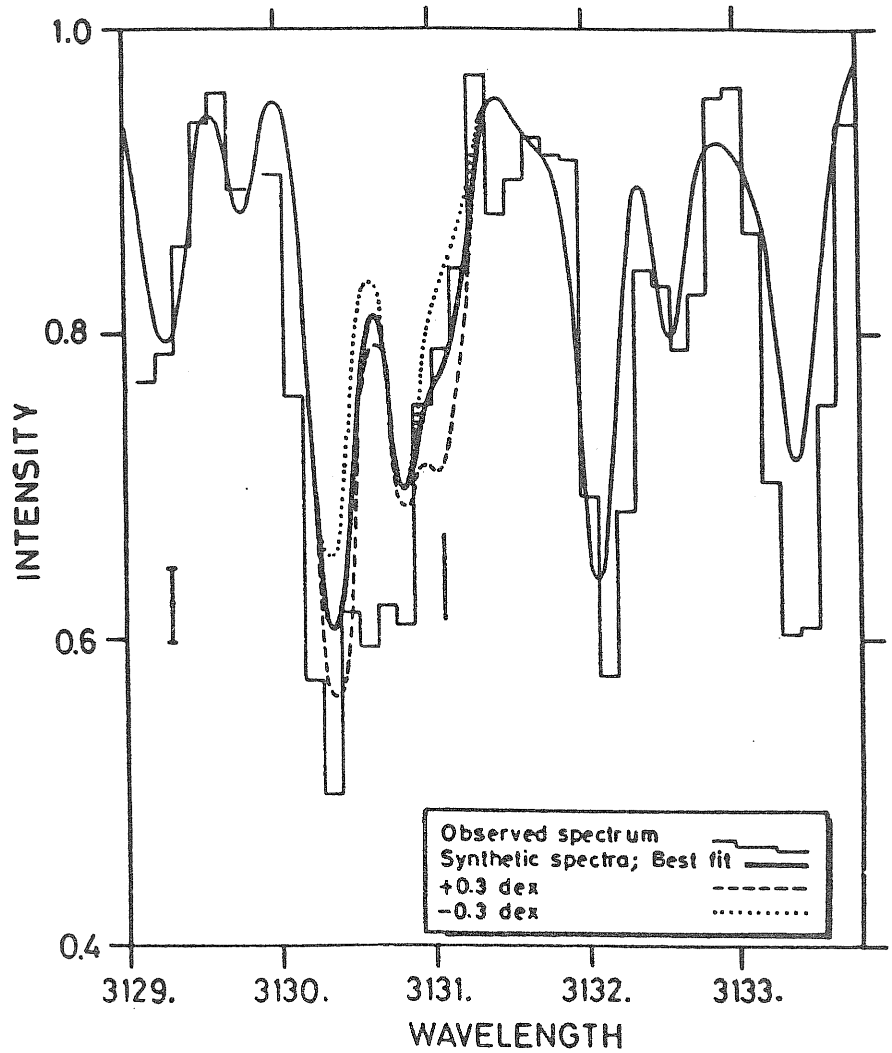


Fig 3.3b As Fig 3.3a It is shown the effect of varying the Be abundance by a factor two either side of the best fit.

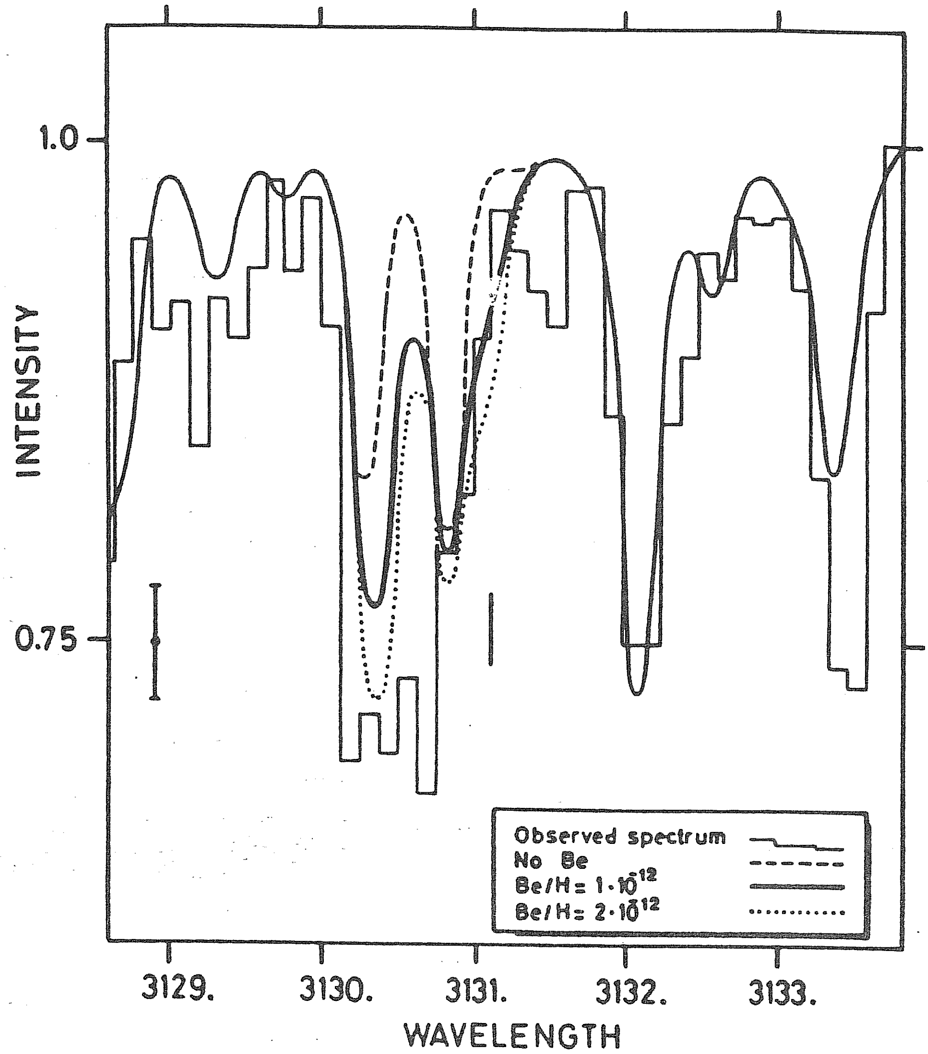


Fig 3.4 Observed spectrum for HD 19445 ([Fe/H]=-2.2)). The synthesized spectra are for no Be, Be/H=10^{-12} and Be/H=2×10^{-12}. This final value is our estimate for the upper limit to the Be/H abundance.

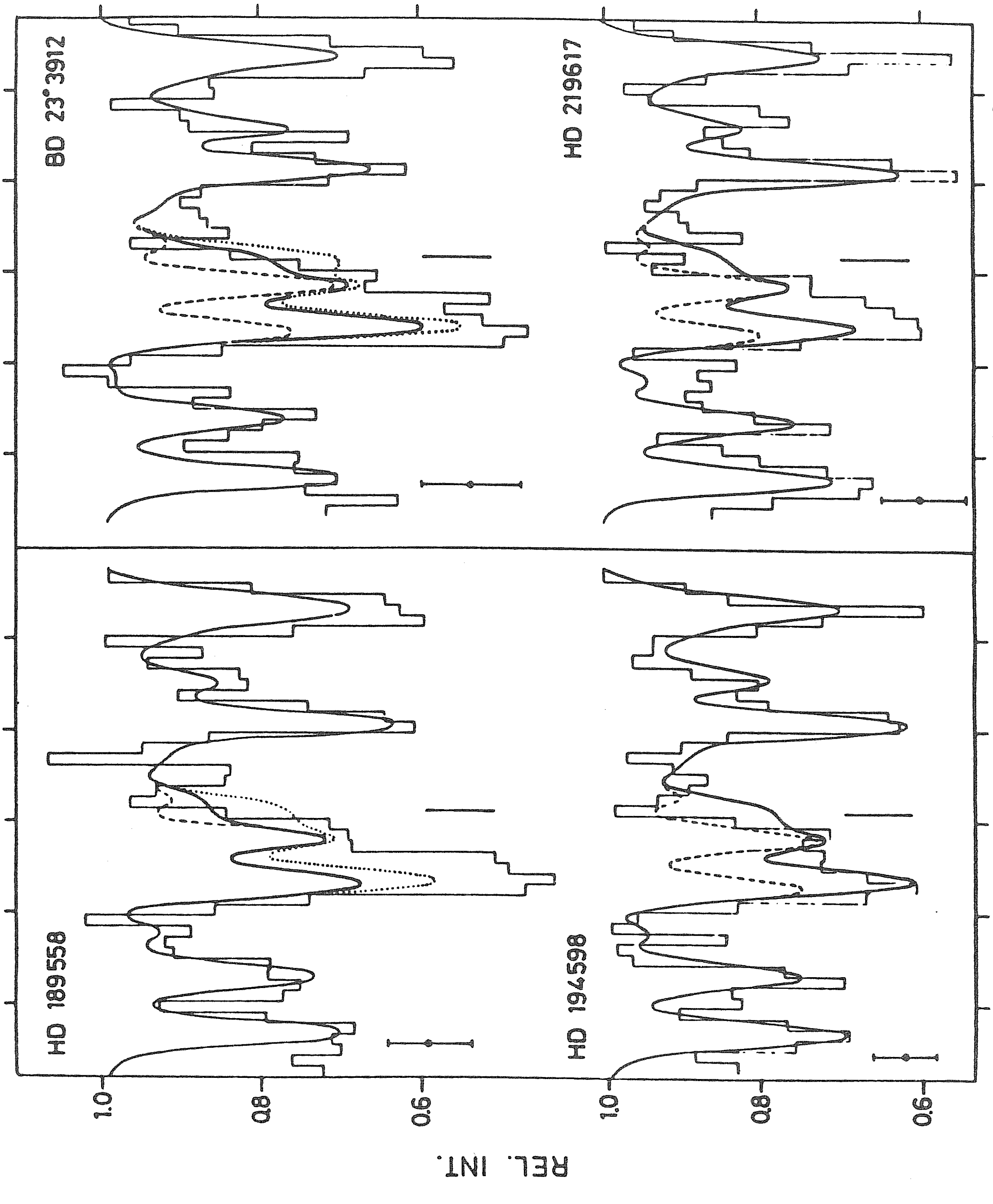


Fig 3.5 Histograms represent the observations. For HD 189558 the models are for Be/H=$1x10^{-12}$, the dashed and dotted lines are -0.4 dex and 0.4 dex respectively. For HD 194598 the continuous line is for Be/H=$2x10^{-12}$ and the dotted line for zero Be/H abundance. For HD 219617 the continuous line for Be/H=$2.5x10^{-12}$ and the dotted line for zero abundance. For BD 23 3912 the continuous line is for Be/H=$2x10^{-12}$) and the dashed and dotted lines are for -0.4 dex and 0.4 dex respectively.

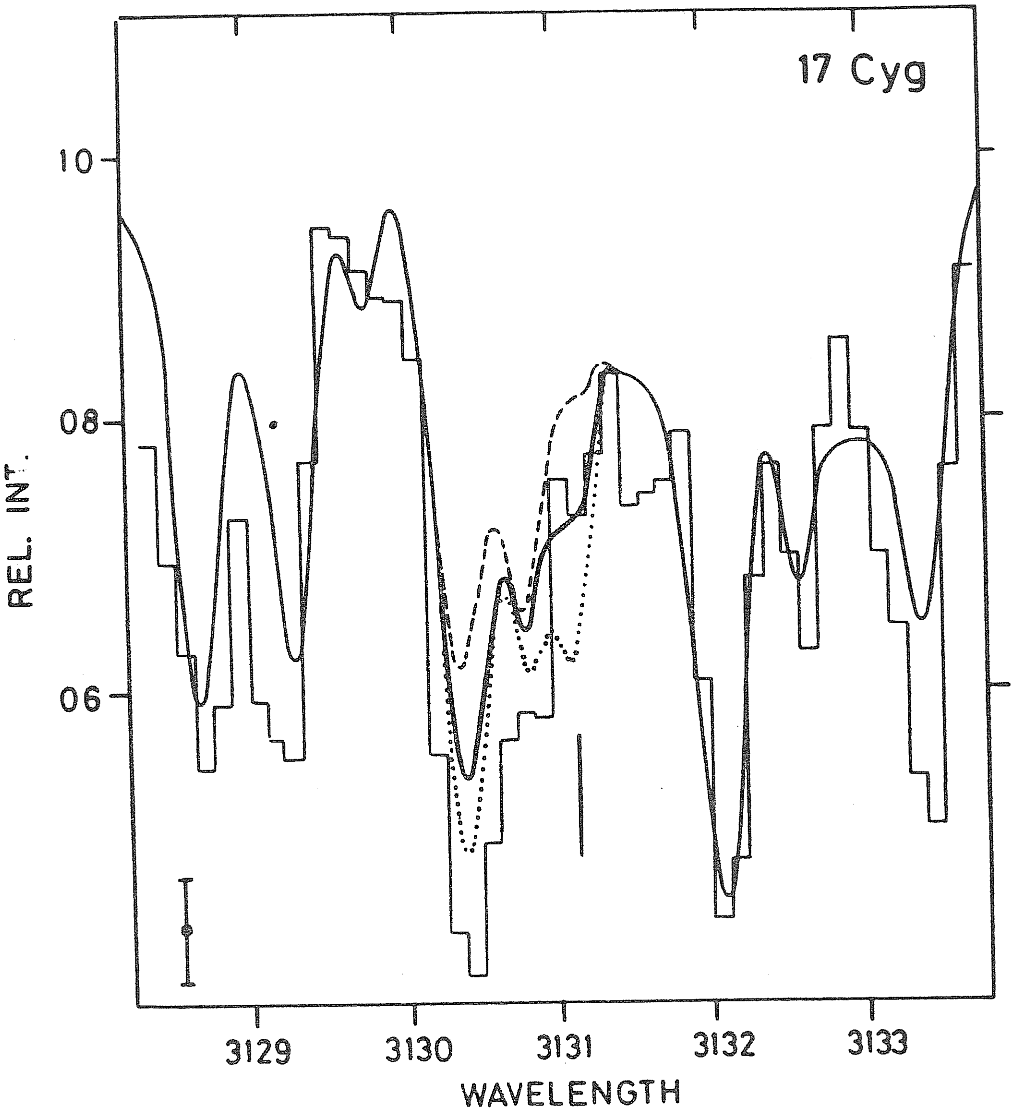


Fig 3.6 The spectrum of 17 Cyg with the synthesized spectra for Be/H=7x10^{-12} (continuous line), Be/H=3x10^{-12} (dashed line) and solar Be (dotted line).

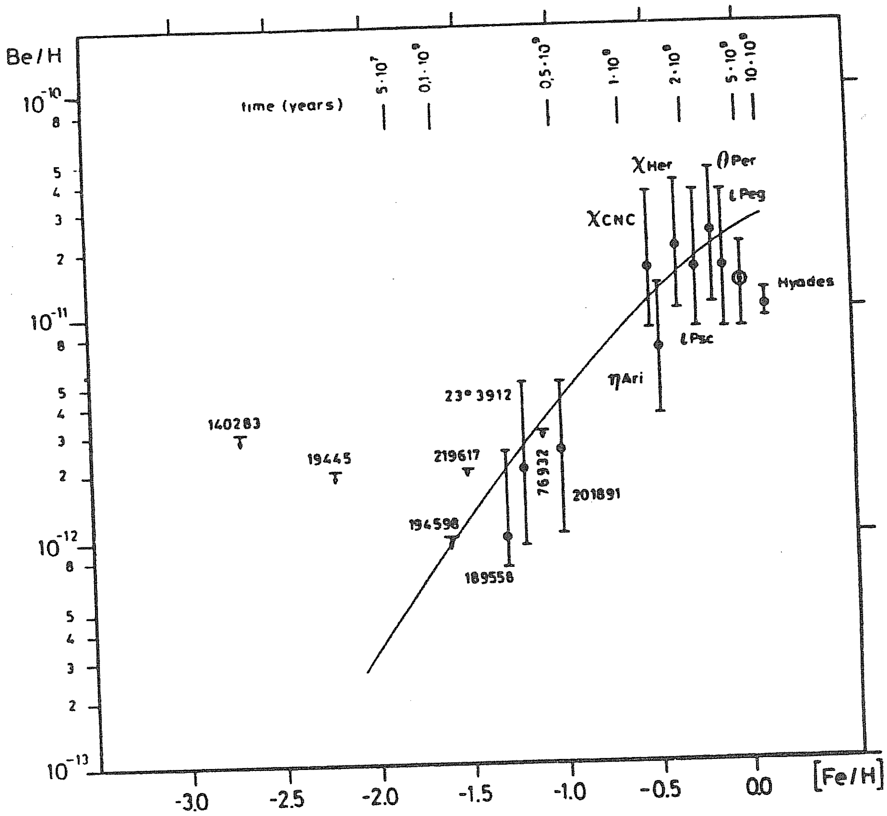


Fig 3.7 Beryllium abundances versus metallicity. Data from the literature and from the present work. The continuous line is for the theoretical model of Abia and Canal (1987).

4. OBSERVATIONS OF BORON IN POPULATION II STARS

4.1 BORON ABUNDANCES IN THE UNIVERSE

Boron is one of most elusive elements in nature, with regard to both astronomical and geological abundance determinations.

Experimental measurements of boron abundances in various meteorites have varied, in the last decade, from values as high as $B/H=5.8\times10^{-9}$ (Cameron et al. 1973) and $B/H=2\times10^{-9}$ (Weller et al. 1977) down to $B/H=3\times10^{-10}$ (Curtis et al.1980). Terrestrial contamination has been generally advanced as the explanation for the discrepancy; nevertheless in the two latter works particular care has been used to avoid such contamination, so it is quite difficult to choose between such different results.

On the astronomical side, the difficulties arise from the intrinsically low abundance of B. B, together with the other light elements Be and Li, is a very rare element, and it is not until we come to Gallium, with atomic number 31, that we find a comparably low abundance. Another crucial factor is that all the resonance lines fall into the UV (BI at 2496, BII at 1362 A and BIII at 2067 A), requiring observations from space, and are in differing degrees affected by blends with many nearby lines. Boesgaard and Heacox (1978) measured B, through the BII 1362 A, in 16 sharp-lined hot stars, of spectral type A and late B, using Copernicus data. The B abundance appears nearly the same in all the stars of their sample, and equal to $2x10^{-10}$ when non-LTE effects were taken into account. So far this represents the most complete and homogeneous set of observations and the abundance they derived is generally adopted as the present boron abundance.

Interstellar boron has been detected in front of k Ori by Meneguzzi and York (1987) and they found $B/H=1.5(+/-0.7)x10^{-10}$ consistent with the value found in the hot stars (see also chapter 5).

Among the cool stars, the sun is the only one for which we have a positive detection of B. Kohl et al. 1977, using solar spectra at the very high resolution of 3 Km/sec, derived $B/H=4(+/-2)x10^{-10}$ from the BI resonance doublet at 2496 A. This value from the ultraviolet is significantly above the upper limit of $B/H< 1.2(+/-)0.6x10^{-10}$ derived by Hall and Engvold (1975) from the absence of the infrared 16240 A BI lines. The discrepancy is greater than the errors mentioned by the authors and, even though not dramatic, tells us that even for the sun we do not know precisely what the boron abundance is.

In other sites boron has been detected in 9 Mn-Hg stars, i.e about 36% of the stars of this type so far investigated for this purpouse (Sadakane et al 1985), and in some of them with large overabundances, up to 1.8 dex, with respect to the "stellar" value. These large values are believed to be associated with the specific chemical properties of these peculiar stars.

Despite these various problems, all these determinations have the merit of showing that boron exists in nature. A list of the more recent determinations of boron abundance in various media is given in Table 4.1

4.2 BORON OBSERVATIONS IN THE POPULATION II STARS

The observational scenario is quite unsatisfactory, with a complete lack of observations in cool stars, where such observations would be more interesting. In fact, it is only from boron observations in cool stars that we can reconstruct the evolutionary abundance curve of boron at epochs preceeding the formation of the solar system.
Depending on what value one chooses for the meteoritic-solar value, the evolutionary abundance curve may be either fairly costant, or may increase or decrease as we go back in time.
Knowledge of the abundances of the light elements, at periods preceeding the formation of the solar system, can be obtained from the atmospheres of old population stars, provided that lithium, beryllium and boron not dragged into the hot interiors by convective motions or by diffusion.

^{7}Li has been extensively observed in the last few years in population II objects showing that it was present before the formation of the Population II. These observations revealed an unexpected survival of Li in the atmospheres of these very old stars, disclosing observational possibilities also for the elements Be and B.
We have discussed the Be observations in the previous chapter and the search for ^{6}Li has been carried out without success by Maurice et al. 1984.

The remarkable paucity of data reflects the difficulties faced in studying boron in cool-stars. The problems encountered in reproducing the spectral region around the 2496 BI lines were clearly evident in the Kohl et al. 1977 paper, discouraging further investigation, since no other attempts have so far been undertaken to derive boron abundances in cool stars.

The most important problem is the severe blending of the BI 2496 A resonance doublet. The BI 2496.779A is blended with the CoI line only at 0.07A, and the stronger BI 2497.725 is hopelessly blended with a strong FeII line only at 0.009 A. Other difficulties are: the uncertainty in placing the ultraviolet continuum, the lack of experimental oscillator strengths, the many missing lines in the ultraviolet region, and the limited S:N today available in ultraviolet data.

IUE is certainly not appropriate for boron observations, while such investigations will fall within the capabilities of the High Resolution Spectrograph on board the Space Telescope. Here we show that some of the above-mentioned problems can be alleviated by analyzing high resolution IUE spectra of very metal-deficient stars. The notable reduction in the line blocking make possible a less ambiguous location of the continuum level and also makes it possible to detect relatively faint lines.

4.3 ANALYSIS OF IUE DATA AND BORON ABUNDANCES

Among the more metal deficient dwarfs or subgiant stars observed with IUE are HD 140283 and HD 76932, with which we have started this investigation. The basic data for the stars and for the observations are reported in Table 4.1.

The IUE images have been taken from the VILSPA archive and the LWR 5345 and LWR 7182 are rather well exposed with about 28000 DN and 20000 DN at 2500A, but the IUE capabilities are not fully exploited, as these observations are not optimized for the wavelength at 2500 A. The original net-ripple corrected data have been slightly smoothed with two triangular filter cycles to reduce high frequency noise. In IUE spectra, the BI 2496 A lines fall at the border of order 93, about 12 A from the edge and an imperfect ripple-correction can produce distortions that must be corrected. Moreover, a reseaux mark falls near the region, and sometimes on the lines, so in addition a certain quantity of good luck is required.

The analysis has been performed using the Synth procedure to compute a synthetic spectrum from the blanketed Kurucz model atmosphere corresponding to the properties of the star under study (Castelli 1985). All the computations have been performed by assuming an LTE approximation.

The line data are mainly those of Kurucz and Peytremann (1975) integrated with other subsequent lists that have appeared in the literature (Kurucz 1981, Wiese and Martin 1980), Kohl et al. (1977) and are given in Table 3, together with the basic nuclear parameters. All the lines have been convolved using a gaussian profile to account for the IUE instrumental profile and all the other broadening sources. The log gf values used for the BI resonance doublet have been taken from Kohl et al. (1977) and are -0.76 for BI 2496.779 A and -0.46 for the 2497.725 A. Theoretical f strengths for the lines have been computed recently by McEachran and Cohen (1982) and are not significantly different.

For the computation of the continuum, all the opacities of H, He, H^-, H_2, and the most abundant elements are considered. In particular, the bound-free absorption of the ^3P level of MgI, with its ionization threshold at 2513 A, which is quite important here, is taken into account.

Wavelength calibration is achieved by matching the observed and synthetic spectra, reducing the wavelength scale to the photospheric frame. Particular weight has been give to the line FeII 2498.90 A which is the closest relatively strong line to the BI doublet.

4.3.1 Boron Upper Limit in HD 140283

HD 140283 is one of the most metal deficient dwarfs known, and one of the most studied, owing to its brighness relative to the other known population II stars. Despite this, its atmospheric are not well established, and the values in the literature differ significantly from one another. In Table 4.2 we report the atmospheric characteristics and abundance determinations of HD 140283 published in the literature.

The synthetic spectrum has been computed using a Kurucz (1979) atmospheric model with Teff=5500 K, log g=3.5, and -2.5 for metallicity. The line spectrum has been computed using [Fe/H] =-2.4 and the microturbolence is 1.5 Km/sec, constant with depth, taken from the detailed analysis of Magain (1984). The synthetic spectrum around 2496 A is fairly insensitive to small changes in the Teff or in log g, making our choice of the model independent of the variety of values in Table 4.2. The lines have been convolved, to account for the IUE instrumental profile, with a gaussian profile with a FWHM of 11 Km/sec.

The observed spectrum around the BI 2496 A lines is shown in Fig. 4.1, together with the synthetic ones with $B=0.1x10^{-12}$, $B=1x10^{-11}$ and $B=4x10^{-10}$.

The computed spectrum is generally weaker than the observed one. An increase in metallicity seems not to be an easy solution, because it produces disagreement in some portions of the spectrum. We are inclined to believe that the general weakness of the computed spectra is due to the presence of many unidentified lines, a well known problem in the ultraviolet. A discussion on the star's metallicity is beyond the scope of the present work and is not crucial for boron analysis. It must be noted that like any non-identified blend, also an underestimation of the metallic content tends to depress the flux in correspondence to the BI lines, making the upper limit we derive even more conservative.

Inspection of the solar spectrum synthesis by Kurucz and Avrett (1981) reveals the presence of many unidentified lines, in particular an unidentified blend around 2498 A is also present. Luckily, the fainter of the two B lines appears unaffected by this problem.

The non-identified feature at 2496.88 A present in the solar spectrum (and quite important in the boron abundance determination of Kohl et al. (1977)), has been treated in the same fashion as an iron group line of 1.0 ev and 6.4 ev of lower and higher excitation potentials respectively and a log gf of -1.2. Another modification concerns the log gf of FeI 2496.992 A reduced from 0.770 to -0.5 to fit the observed flux. This reduction is also justified by the fact that this line is too strong in the solar spectrum synthesis of Kurucz and Avrett (1981). Other slight differences are explicable by the use of a single value for metallicity derived for iron that cannot be applied to all the elements uniformly.

The uncertainty in the definition of the local continuum is as usual one of the critical points, but here it is less severe because the low metallicity of the star acts to reduce significantly the line-blocking. In the present analysis we assumed that the local continuum passes through the points at 2493.5 A and at 2499.5 A, which are the highest points of order 93 near the B lines.

From the figure it is possible to see that the computed spectrum with a value for B of $4x10^{-10}$, the solar value, gives two lines that are much stronger than the corresponding observed spectrum. Taking into account the uncertainties, a conservative upper limit can be placed at $B < 1x10^{-11}$, i.e. 40 times less than the solar value, while the synthetic spectrum with $B=0.1x10^{-12}$ gives the best fit. In particular in correspondence to the BI line at 2496.772 the difference in flux is about 30% in both figure 4.2a and 4.2b, surely greater than any plausible noise fluctuation or uncertainty in the continuum location. The isotope wavelength splitting is only 0.008 A, so the upper limit derived here is an upper limit for the sum of ^{10}B and ^{11}B.

4.3.2 Other Population II stars observed with IUE

HD 76932

The metallicity of this star has been studied by Barbuy

(1978) and is practically constant for all the more abundant species. The metallicity, even if less than one-tenth of the solar value, is considerably greater than that of HD 140283 and this results in a notable enhancement in the line blocking.
The synthetic spectrum has been computed from a model with Teff = 5860 K, gravity log g=3.5 and a microturbolence of 1 Km/sec. In this case the van Der Waals constants of the strong lines, such as FeI 2491.155 A, have been increased by up to a factor of 5 over classical values in order to obtain better fits of strong lines. The synthetic spectrum has been integrated over a large range to take into account the contribution on the wing of the FeI 2491.155 A strong line.

Fig. 4.3 shows a preliminary analysis of the synthetic spectrum around BI 2496 A. As expected owing to the increase of the metallicity, the disagreement between the synthetic spectrum and the observed one is greater than in HD 140283. The region around the BI lines is zoomed in Fig 4.4. The log gf values of the three strong Fe lines near the BI doublet are reduced similarly to what has been done for HD 140283. This reduction is quite ad hoc and precludes the use of the 2497.725 for B analysis.
Unlike the case of HD 140283, from Fig 4.4 is possible to see that an absorption is present in correspondence to 2496.7 A. This can be ascribed to B, but also to an unidentified line located at 2496.88 A, which is present in the solar spectrum and noted by Kohl et al 1977.
There is no way to account here for the unidentified line and we must wait for better resolution data in order to solve the problem. At first glance we attribute this contribution to the

B line. The absorption is consistent with an abundance of $B/H=2x10^{-10}$ that we consider as an upper limit to the possible presence of B.

HD 216385

This star, with [Fe/H]=-0.6, can be considered representative of moderate metal-deficent stars. The synhtetic spectrum is performed with Teff=6070 logg=4.0. Fig. 4.5 gives the sintetic spectrum with $B/H=1x10^{-12}$ and $B/H=4x10^{-10}$. As can be seen from the figure, no appreciable difference is observable between the two cases; thus we cannot infer any B abundance with the present data. This case is illustrative of what happens as the metallicity of the star increases and also of the difficulties that one faces in trying to derive B abundances in cool stars with solar abundances.

4.4. GALACTIC EVOLUTION OF BORON

Of LiBeB, boron is the most refractory element, being destroyed by thermonuclear reactions at higher temperatures. In the star under study Li has been observed (Spite and Spite 1982, Beckman et al. 1986) and its presence is a guarantee against significant depletion of the more refractory B. Moreover as described in detail previously F. Spite and M. Spite (1982) have argued that the absence of any depletion is the most logical way to explain the constancy of the ^7Li observed in all the extreme metal-deficient dwarfs, and this should hold for B too. Since HD 140283 is one of the dwarfs most deficient in metals and thus one of the oldest known, the present observation implies an absence of B in the galactic gas before the formation of the pop II generation.

The two stars studied here provide some evidence of a low B abundance in the atmospheres of stars older than the sun. This is a circumstance that suggests a gradual increase of this element, starting with zero values at the beginning of the galaxy. This seems consistent with the view that the light elements are produced by spallation processes in the interstellar medium and make their synthesis in pregalactic events unplausible, as the "little bangs" model proposed by Wagoner (1969).

Reeves et al (1970) suggested that LiBeB could be mostly made in the early days of the Galaxy, when the events of nucleosynthesis were more frequent and presumably the GCR fluxes more intense. Indeed detailed models which assume an enhancement of the star formation rate close to the initial epoch of the galaxy predict the synthesis of large quantities of B up to 10^4 within the first billion of years, nearly four orders of magnitude above the present upper limit; afterwords these large quantities decreased to present values by astration and infall of extragalactic primordial matter (Audouze and Tinsley 1974). In Fig 4.6 is shown the recent theoretical computation for boron of Abia and Canal (1987).

The present upper limit favours the models of Meneguzzi et al. 1971 and Truran and Cameron (1971),with a smoother augmentation of B abundance through time. Strictly speaking, a rapid build-up of B abundance is still possible if HD 140283 was one of the first stars formed in the Galaxy before there was any detectable formation of B.

If one takes the extreme models of Audouze and Tinsley (1974) a time interval of less than 10^8 is sufficient to make $(^{10}B+^{11}B)=1x10^{-11}10$, i.e. on the order of the present upper limit. Thus, either one or more of the conditions required to produce B is missing or Population II was formed very early. A suggestion in this second sense has been made recently on theoretical grounds by Cayrel (1986). Anyway observations extended to objects with higher metallic content than HD 140283 are needed to put tighter constraints on various models for early galactic evolution.

4.5. IMPLICATIONS FOR THE ORIGIN OF LITHIUM IN POPULATION II STARS

The substantial absence of B in the protonebula put firm constraints on the nucleosynthetic processes for the observed Li. The difference in the nucleosynthesis mechanisms for these two elements enables the use of B determination to control the fraction of ^{7}Li that can be produced by spallation processes. In particular it is interesting to examine the possibility that enhanced spallation could have produced the bulk of ^{7}Li observed in Population II . This possibility is highly speculative, since we do not know the physical conditions of the young Galaxy but it results from models that assume enhanced star formation in early epochs.

Unfortunately, the present upper limits of B cannot help to solve the main question, whether some lithium has been depleted in the atmospheres of the Population II stars.

In HD 140283 Spite and Spite (1982) derived a ^{7}Li abundance of 95, Beckman et al. (1986) substantially confirmed their value deriving 107, and Hobbs and Duncan (1987) found 126. Combining these determinations with the upper limit for B derived here the resulting ratio is

$$Li/(^{10}B+^{11}B) > 10$$

Following the recent evaluation of Walker et al. (1985), the expected ratio coming from the spallation theory of high energy cosmic rays is

$$Li/(^{10}B+^{11}B) = 0.4$$

The observed ratio is more than 25 times higher than the predicted one. Unlike absolute quantities, ratios between light elements depend only on the GCR spectrum shape and not on the variation in intensity of the cosmic ray flux or the behavior of the chemical evolution of the galaxy.

The upper limit of $B=1x10^{-11}$ derived here implies that, even in the presence of depletion, less than 4% of the Lithium observed in the population II star can potentially be produced by spallation processes and another 2% can be in the form of Li, which is observationally almost indistinguishable from Li. The observed ratio $^{7}Li/B$ strongly argues against the possibility that an early enhanced spallation could have produced the Lithium observed in the Popilation II stars.

The conclusion derived here from the upper limit of B is by far more stringent than the constraint that comes from the absence of Be in this star (see previous chapter). This results from the large cross section of B that makes it the most probable output of spallation reactions.

The above discussion is limited to GCR with energies above 100 Mev for which we know the spectrum. With regard to the low energy component, the existence of suprathermal particles with energies of a few Mev favours B production. The threshold of the reaction $^{14}N(p,^{4}He)^{11}C(e^{+})^{11}B$ is = 3 Mev and that of reaction $^{13}C(p,^{4}He)^{10}B$ is about 4 Mev, while the thresholds for producing ^{7}Li and Be are greater than 10 Mev. In particular, particles with energy of < 8.5 Mev per nucleon make much more B than Li, but the reverse happens with particles with E > 9 Mev per nucleon.

The presence of a low energy component is not established owing to the problem of solar demodulation, but is usually added in the cosmic rays to explain the observed isotope ratio of $^{11}B/^{10}B=4.0$ (Meneguzzi et al. 1971; Walker et al. 1985). The present observed ratio rules out a significant synthesis of ^{7}Li via a low energy component in the past GCR, unless this component has the appropriate energy to produce more ^{7}Li than B. This also leads to the conclusion that nearly all the ^{7}Li of Population II must be produced in ways other than spallation.

The remarkable coincidence between the predictions of the canonical Big Bang and the observations, together with the high uniformity of the ^{7}Li abundances among the Population II, which reflects also an uniformity of space in the early Galaxy, make the big bang the leading hypothesis to explain the production of ^{7}Li in Population II.

Boron is produced in the canonical big bang at a baryon density near the value needed to close the universe (Wagoner 1973). Its maximum value reaches 0.7 for a $\rho \sim 10^{-28}$ g/cm^{-3} (T = 2.7 °K), but it is also sensitive to the acceleration in the expansion of the universe, increasing with it (Wagoner 1973), and thus with the number of neutrino species. Its maximum production is about one order of magnitude lower than the present upper limit. If, in the near future, more precise B observations are available with the High Resolution Spectrograph on board Space Telescope, these will offer a new and valuable means to consider the possibility of a universe with a density close to the critical one.

source	B	references
stars	$2(+/-2)x10^{-10}$	Boesgaard and Heacox 1978
meteorites	$2x10^{-19}$	Weller et al 1977
	$3(+/-2)x10^{-10}$	Curtis et al. 1980
sun	$4(+/-2)x10^{-10}$	Kohl et al. 1977
	$<1.8x10^{-10}$	Hall and Engvold 1975
	$<3x10^{-10}$	Engvold 1970
	$<2x10^{-10}$	Wohl 1974
interstellar	$1.5(+/-0.7)x10^{-10}$	Meneguzzi and York 1980
	$<7.6x10^{-11}$	Morton 1975

Table 4.1. Boron determinations in various media.

HD	Teff	logg	log[Fe/H]	Ref
140283	5730	3.3	-2.4	Spite and Spite (1978)
	5600	3.25	-2.36	Peterson (1976)
	5600	4.0	-2.60	Peterson and Carney (1979)
	5730	3.3	-2.4	Spite and Spite (1980)
	5600	4.0	-2.6	Peterson (1981)
	5470	3.3	-3.0	Magain (1984)
	5740	3.5	-3.0	Cacciari et al.(1986)
	5645	-	-2.81	Laird et al. (1986)
76932	5861	3.5	-1.1	Barbuy (1978)
216385	6072	4.0	-0.6	Hearnshaw (1974)

Table 2. Effective temperature, gravity and metallicity of the stars under study from the literature.

	LEP	HEP	Logf	S	ION
2496.309	0.983	5.948	-0.440	K	Cr I
2496.534	0.915	5.879	-0.721	KP	Fe I
2496.640	0.580	5.546	0.500	KP	W II
2496.707	0.514	5.478	-0.759	KP	Co I
2496.779	0.000	4.964	-0.760	KW	B I
2496.870	1.000	6.400	-1.20	art	?
2496.992	2.559	7.523	-0.500	KP	Fe I
2497.303	3.221	8.184	-1.120	K	Fe II
2497.480	0.750	5.714	0.31	KP	W II
2497.683	2.807	7.769	-1.851	K	Fe II
2497.716	3.267	8.229	-1.412	K	Fe II
2497.725	0.002	4.964	-0.460	KW	B I
2497.802	1.859	6.821	-2.482	KP	Ni II
2497.814	3.230	8.192	0.053	KP	Fe II
2497.820	2.844	7.806	-2.616	K	Fe II
2497.820	3.230	8.192	0.024	Kn	Fe II
2497.960	0.000	4.963	-1.440	WM	Ge I

Table 4.3. List of the lines used in the synthetic spectrum. KP are Kurucz Peytremann (1975), K is Kurucz (1981), KW are Kohl et al. (1977), WM are Wiese and Martin (1980), art is the unidentified line, Kn are lines taken from Kurucz but not present in the original KP list.

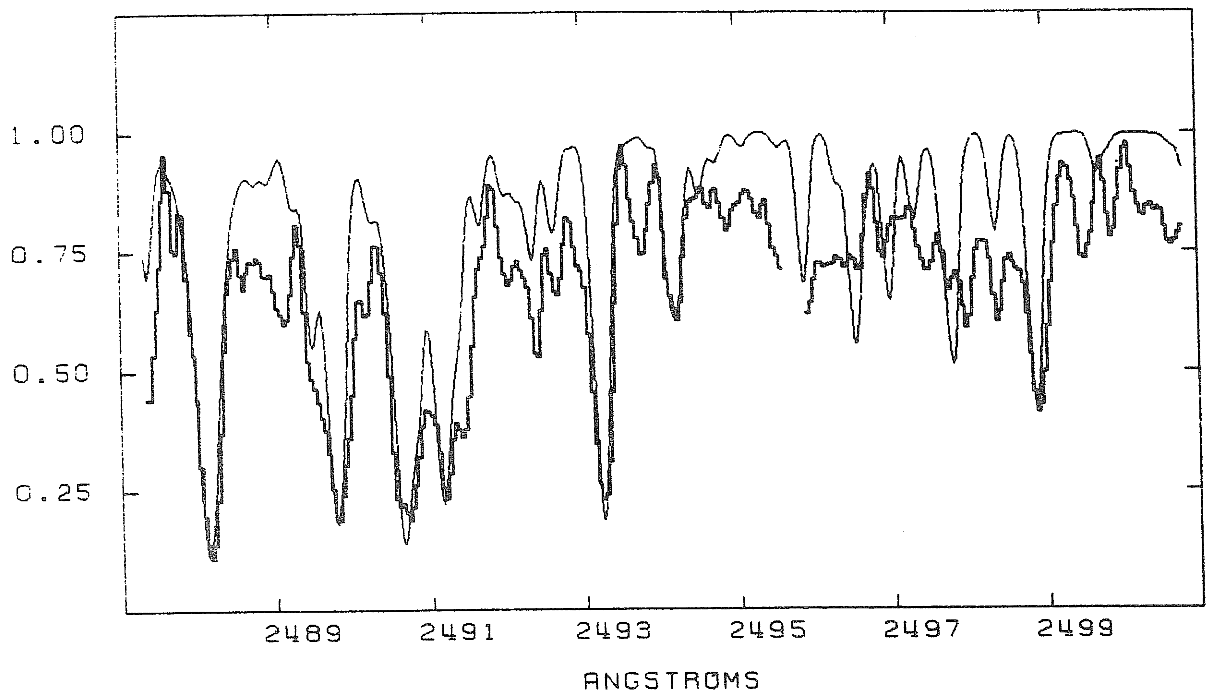


Fig 4.1. Observed (histogram) and the synthetic spectrum corresponding to the atmospheric model for HD 140283 described in the text. $B/H=0.1x10^{-12}$. The gap at 2496 A is due to the presence of a reseaux-mark.

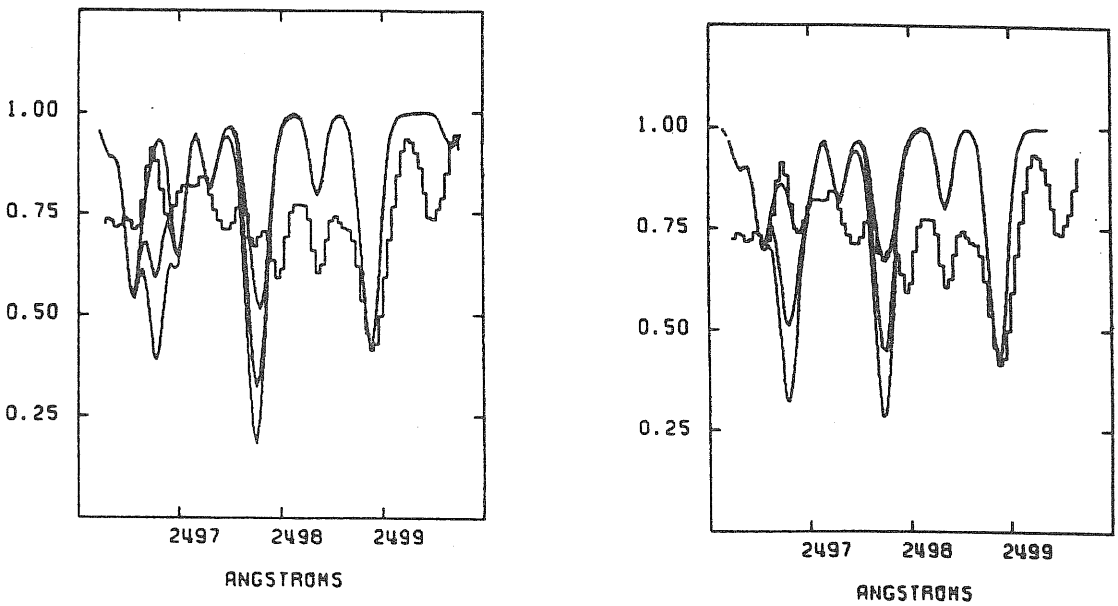


Fig 4.2 The same as in Fig 4.1, zoomed around the BI lines. The three synthetic spectra are with three different B abundances: $B=0.1x10^{-12}$, $B=1x10^{-11}$, $B=4x10^{-10}$ in order of increasing intensity. On the right after modification of some log gf values.

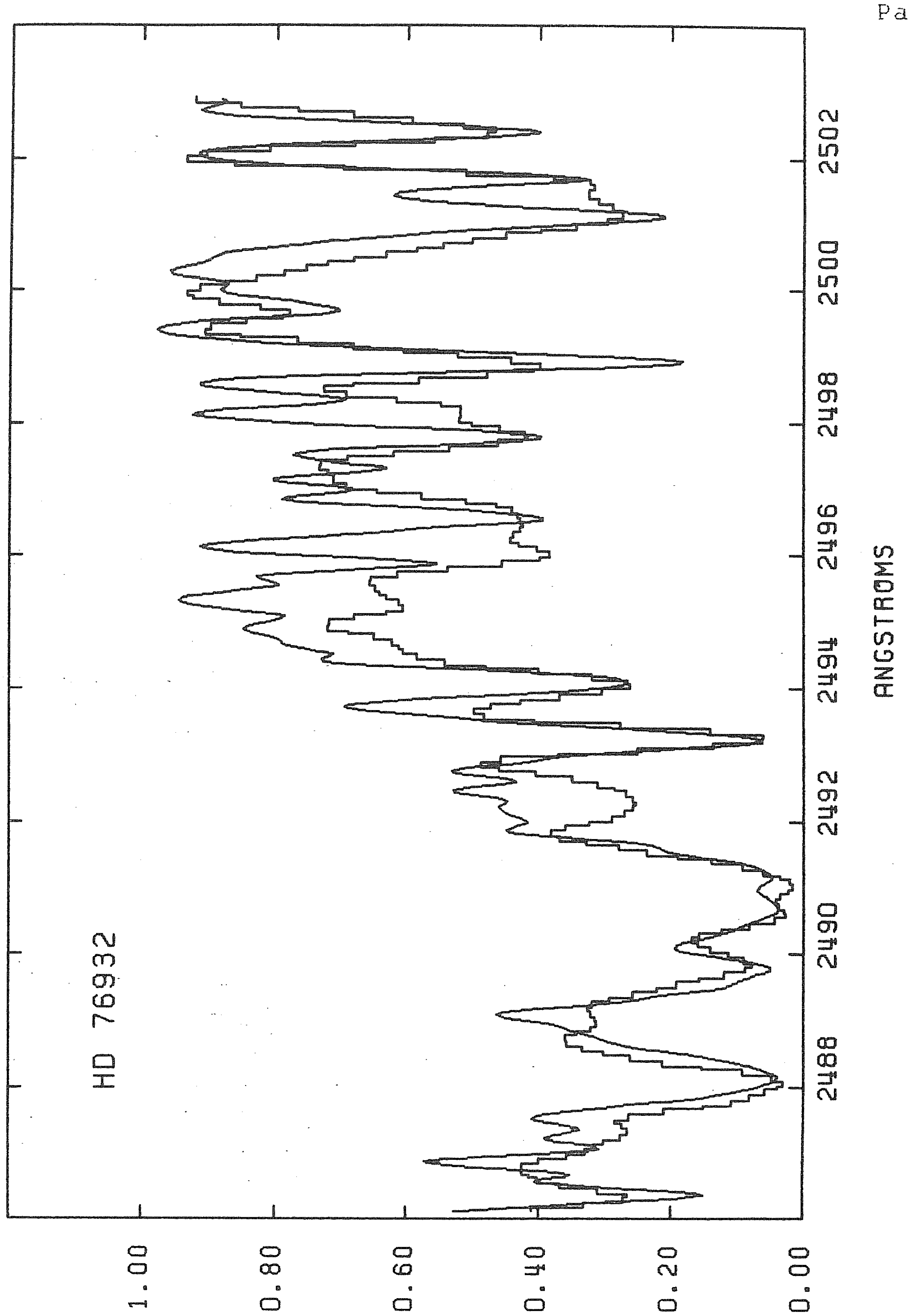


Fig 4.3 Observed (histogram) and synthetic spectrum for HD 76932 around the BI 2496 A.

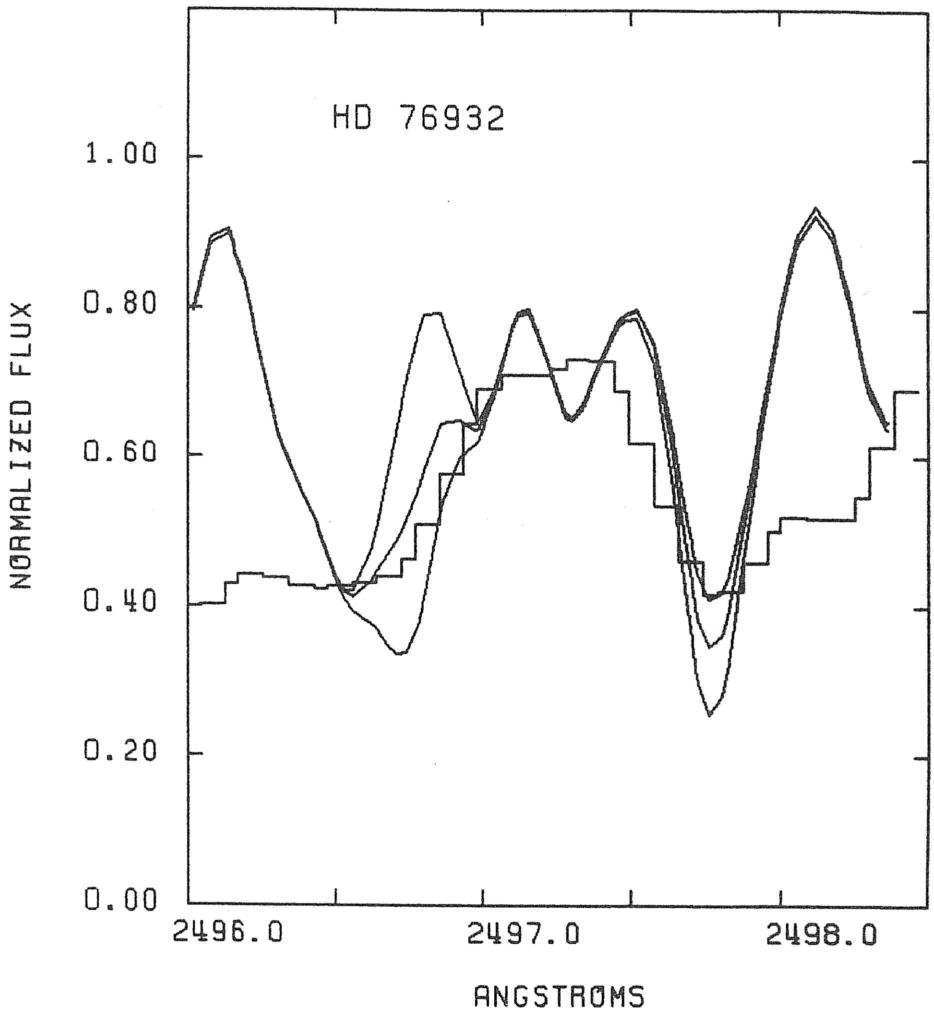


Fig 4.4 The same as Fig 4.3 zoomed around BI lines. The models are for $B/H=1x10^{-12}$, $B/H=2x10^{-11}$ and $B/H=2x10^{-10}$

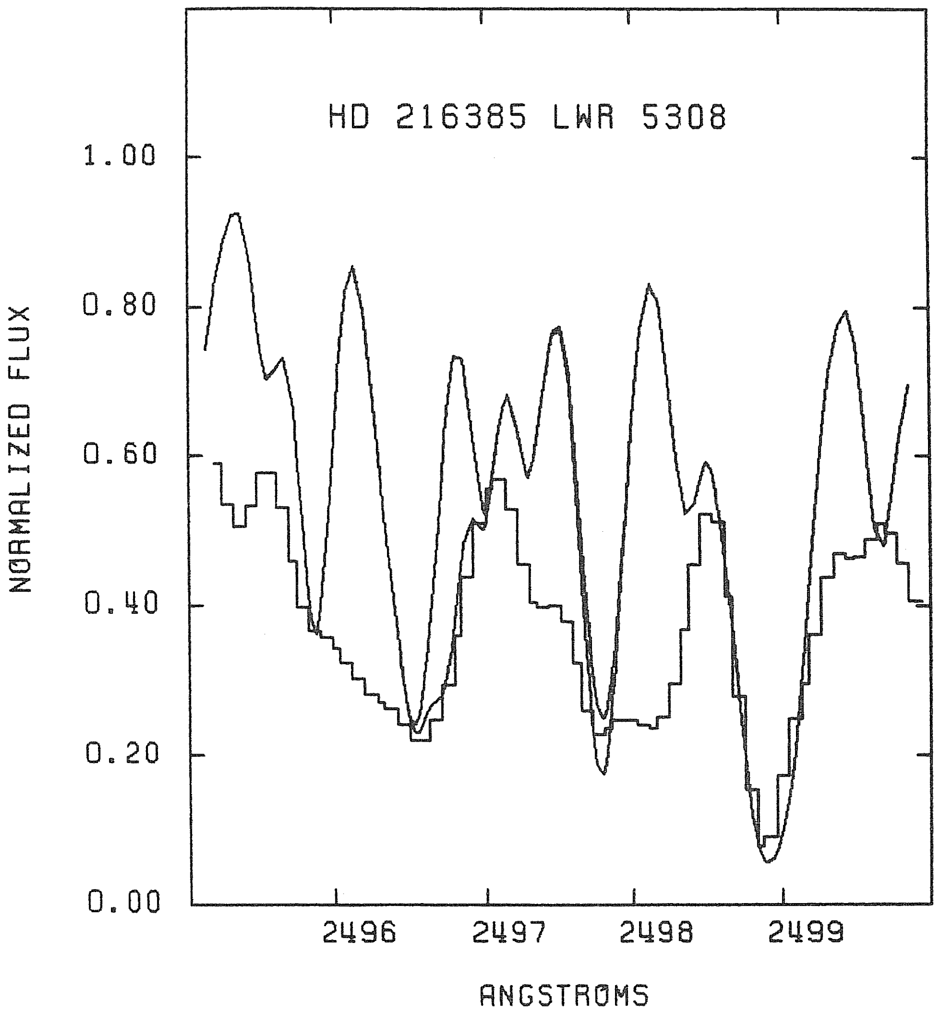


Fig 4.5 As fig 4.1 for HD 216385. The models are for $B/H=1x10^{-12}$ and $B/H=4x10^{-10}$.

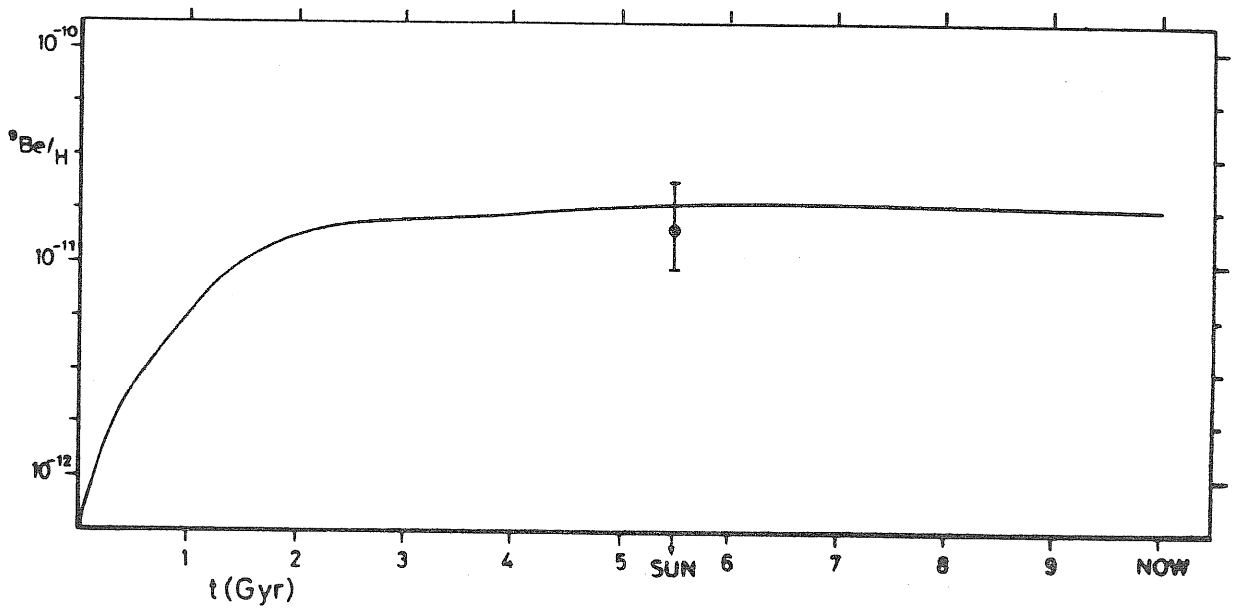


Fig 4.6 Theoretical production by high energy cosmic rays of boron From Abia and Canal (1987)

5. INTERSTELLAR LITHIUM, BERYLLIUM AND BORON IN THE LMC

5.1 INTERSTELLAR OBSERVATIONS OF LITHIUM, BERYLLIUM AND BORON

Interstellar observations provide information on present cosmic abundances and on the amount of depletion suffered by these elements in the interstellar gas.
The depletion expected for B and Be is markedly different in the various theories of grain formation making these elements possible discriminants among depletion models (Chaffee and Lutz 1977). On the contrary, Li, as well as the other alkali elements Na and K, is predicted not to be strongly depleted both in the grain-condensation hypothesis or in the grain-accretion one (Field 1974, Snow 1975).

Interstellar lithium has been extensively searched for in our own galaxy but only rarely found (Traub and Carleton 1973, Vanden Bout and Grupsmith 1974, Vanden Bout, Snell, Vogt and Tull 1978, Snell and Vanden Bout 1981, Hobbs 1984, Ferlet and Dennefeld 1984, White 1986). To our knowledge only 9 detections and some upper limits are reported in the literature, all at a typical W less than or equal to lmA.

For B only a few lines of sight have been investigated and so far only one positive detection towards kOri (Meneguzzi and

York 1980), a part from a few upper limits (Audouze et al. 1973, Morton et al. 1974, Morton 1973, Morton 1978, Snow et al 1979, Cardelli Bohm-Vitense 1982). The most stringent of the upper limits is that towards Oph which is significantly lower than the detection towards kOri implying a variation either in boron abundance or boron depletion by a factor of 5 between the two lines of sight. Search for interstellar B lines has been carried on for several QSOs (Baldwin et al 1977, and references therein). In the best cases the upper limits have been placed at 110mA.

For BeII only upper limits exist in the literature (Herbig 1968, Boesgaard 1974, Chaffee and Lutz 1977, York Meneguzzi and Snow 1982, Boesgaard (1985). The most stringent cases show that Be is depleted by factors of at least 2-3 below the solar value of $1.3x10^{-11}$.

5.2 INTERSTELLAR LITHIUM, BERYLLIUM AND BORON IN THE LMC

The observation of these elements in an external galaxy provides clues of such particular nucleosynthesis processes in an environment different from the galactic one. In particular it is of interest to look at the ^{7}Li abundance in a less evolved galaxy such as the LMC and to compare it with the standard Big Bang nucleosynthesis yields.

Determination of the abundances of these elements in the stellar atmospheres are far beyond the present observational capabilities and Supernova Shelton has offered a unique possibility to search for these elements in the interstellar spaces of the Large Magellanic cloud.

A claim of a detection of ^{7}Li lines in spectra of SN 1978A, one at galactic velocities and two at LMC velocities, has been recently reported (Vidal-Madjar et al 1987). This detection has been recently criticized by Baade and Magain (1987) arguing that the primordial $^{7}Li/H$ abundance is as low as $1x10^{-10}$. We show here that the galactic detection at 0.2 mA is at the level of our limiting W while of the two Magellanic components at 0.5 mA and 0.3 mA, at least the stronger is not supported by our data. The low value for LiI implied by our upper limit is discussed here with regards to lithium depletion and the possible present Lithium abundance in the LMC.

5.2.1 Observations of SN1987a and Data Reduction

Observations of the spectral region around LiI 6707A were taken on the night of February 27th using the Reticon detector with the Coude\` Echelle Spectrograph (CES fed by the 1.4 m Coude\` Auxiliary Telescope at ESO, La Silla). The resolving power was selected at the maximum available (10^{5}), corresponding to an instrumental FWHM of 3 km/sec. The exposure was at nearly the saturation of the Reticon so as to obtain the maximum signal to noise in one single exposure. The spectrum was corrected for the Reticon read-out noise and divided by the average of 4 flat fields. The spectrum was calibrated in wavelength using a thorium lamp, and the internal accuracy of the wavelength calibration is of order of one tenth of the resolution. Normalization was achieved using a second order polynomial fit.

The ^7Li region is shown in Fig. 5.1 and the arrows point to the galactic and LMC positions of the main components observed for CaII and NaI. The peak-to-peak variation is 0.3% and the minimum W is 0.3 mA.

For the B we used IUE spectra taken in the high resolution mode with the short wavelength camera. The BII resonance lines lie far in the UV at 1364 A and only the overexposed SWP images taken in the first days immediately after the explosion and before the prompt reddening of the supernova have enough flux. We analyzed the SWP 30381 and SWP 30383, with about 15000 DN each in the region. All the other SWP spectra have less than 5000 DN and are underexposed. The two spectra have been smoothed using a 3 pixel triangular filter, and summed together, with the DN as weights, in order to increase the signal-to-noise ratio. The mean spectrum is shown in Fig 5.2. The observed peak-to-peak variation in the B region is 16%. Considering that the resolution is 0.11A we have a minimum detectable W of 18mA.

The Be resonance doublet is at 3130A and we have used IUE LWP images added together. The minimum detectable equivalent width is about 10mA. Even with the serious atmospheric absorption this region is accessible from the ground, but only very few telescopes in the southern hemisphere are equipped to observe in this region with the appropriate resolution. This limit can be improved using ground observations.

5.2.2. The Lithium Galactic component

In the optically thin line approximation the equivalenth width is related to the column density by the relation

$W = \frac{\pi e}{mc} f \lambda N$ where N is the column density of Li, and f is the oscillator strength. For the LiI 6707 A we have taken f=0.75 (Wiese et al 1966). The upper limits established in the previous section yields a column density for lithiun lower than 1.0×10^{8} cm^{-2} for both the Galactic and LMC components.

Lithium in the interstellar gas is mainly ionized by ultraviolet radiation shorter than 2300 A and the ionization balance for lithium is given by:

1) $$N(Li) = N(LiI) \frac{\Gamma_{Li}}{\alpha_{Li} n_e}$$

where the G and a are the photoionization and recombination coefficients, and ne is the electron density. A simultaneous measurements of N(CaI) and N(CaII) provides the electron density, by means of the photoionization equilibrium equation:

2) $$n_e = \frac{\Gamma_{Ca}}{\alpha_{Ca}} \frac{N(CaI)}{N(CaII)}$$

Considering the similar ionization potential of ^{7}Li (5.4 eV) with K (4.3eV) and Na (5.1eV) we can also write:

3) $$N(Li)/N(X) \simeq N(LiII)/N(XII) = N(LiI)/N(XI) \frac{\Gamma_{Li}\,\alpha_X}{\Gamma_X\,\alpha_{Li}}$$

where X represent K or Na. Towards the supernova both these elements are observed, but Na show saturation effects in the strongest components.

Using (2), N(CaI)=3.2 $\times10^{9}$, N(CaII)= 3.3×10^{11} cm^{-2} from Vidal Madjar et al (1987), $\Gamma_{Ca}=1.98\times10^{-10}$ (Black 1982) and $\alpha_{Ca}=7.7\times10^{-12} cm^{3}s^{-1}$ (Black 1975) we obtain for the electron density the relatively high value of 0.26 cm^{-3}. When $\Gamma_{Li}=3.34\times10^{-10}$ s^{-1} (Caves and Dalgarno 1972) and

α_l =8.2x10^{-12}cm^{3}s^{-1} (Black 1975) are used in eq. (1) the total gaseous ^{7}Li abundance is <1.65x10^{11}.

The HI column density can be derived from the N(H)/E(B-V)=5.8x10^{21} atoms cm^{-2} (Bohlin Savage and Drake 1978) adopting a E(B-V)=0.05 that is observed in foreground stars. This yields N(HI)= 2.9x10^{20} cm^{-2} and so ^{7}Li/H<5.7x10^{-10}. This upper limit imply that lithium is at least a factor of 2 depleted with respect to the "cosmic" value of 1x10^{-9}.

Doing the same computation for K, with Γ_k=6.6x10^{-11} s^{-1} (Black 1982) and α_k=7.0x10^{-12}cm^{3}s^{-1} (Black 1975) from the observed galactic component N(KI)= 4.9x10^{10} cm^{-2}, we obtain K/H=7.4x10^{-9}. This implies for K a depletion by a factor 15 with respect to the solar value of K/H=1.1x10^{-7} (Withbroe 1971).

In the Galaxy the depletion of K is nearly identical to that of ^{7}Li and the 10 lines of sight yield a mean of <log(Li/K)>=0.06+/-0.08 (White 1986). Assuming ^{7}Li is depleted as K the expected Li column density is around 6x10^7; that should produce an W of 0.03mA, i.e. one order of magnitude lower than our upper limit and of the claimed detection by Vidal-Madjar et al (1987) . This fact is also reflected in the N(LiI)/N(KI) ratio. The N(Li)/N(KI) is remarkably constant in the galaxy with 0.0023<N(Li)/N(K)<0.0057 (Hobbs 1984) while in the LMC the N(LiI)/N(KI) derived here is < 0.021.

In conclusion, unless the line of sight to SN1987A is considered to be exceptionally high for lithium, the presence of a lithium line should be lower by one order of magnitude than our upper limit.

5.2.4. The Lithium Magellanic Component

In the Magellanic Cloud towards the supernova the total hydrogen column density can be estimated from $N(HI)/E(B-V)=1.9x10^{22}$ obtained by De Boer et al 1980 in the 30 Dor nebula. Assuming an E(B-V)=0.15 for the reddening towards the supernova due to the LMC from a total E(B-V)=0.20 estimated by West 1987, we derive $H=2.9x10^{21}$. Direct estimation towards the SN1987A gives $N(HI)=2.6x10^{21}$ (Wayte 1987) and in the following we adopt this value.
It is worth noting that in the Galactic lines of sigth with similar column densities ^7Li has always been detected at a level of about 1 mA, while here our upper limit is three times lower.

If we use the relation (2) to estimate the total N(Li) taking $N(CaI)=4.7x10^9$ cm^{-2} and $N(CaII)=5x10^{11}cm^{-2}$ from VAFLV we find $ne=0.24cm^{-3}$ and this gives $N(Li)<1.65x10^{11}cm^{-2}$. With the assumed hydrogen column density this gives $^7Li/H<6.3x10^{-11}$. The situation is summarized in Table 5.1. The interpretation of this upper limit requires knowledge of the present ^7Li abundance and its depletion in the LMC.
From the observations we do not know what is the present stellar lithium abundance since for cool stars, where it can be observed, the abundances are far below the present observational limits. Theoretically the present ^7Li abundance is a particularly difficult prediction since lithium synthesis is a quite complex one, and not clearly settled even in our own Galaxy. In fact it is not clear what is the relative contribution between the primordial synthesis and the galactic

one. The latter, if present, is not related in a simple manner with the other metal abundances.

As discussed in detail in the chapter dedicated to lithium different arguments have been advanced in favour of a primordial $^7Li/H$ abundance of 10^{-10} and alternatively of 10^{-9} (Boesgaard and Steigman 1985). If the primordial production of Li is 10^{-10} a considerable galactic production is required to reach the 10^{-9} observed in young objects. This galactic production can be provided by red giants and novae (Audouze et al 1983) and there is no reason to exclude the same mechanisms in the LMC expecially considering the high frequency of carbon giants observed in the clouds (McCarthy 1987). If the primordial ^7Li production is 10^{-9} then the present ^7Li abundance in the LMC should be the same as in our own galaxy. So in both cases we might expect a present interstellar ^7Li comparable to the galactic value, something around 10^{-9}.

The second problem is the real amount of ^7Li depletion in the LMC. Theoretically ^7Li is not expected to be significantly depleted in the interstellar clouds. Nevertheless in the Galaxy the ^7Li depletion seems very sensitive to the line of sight ranging from a factor 2 to 20, and with an average value of a factor 4 (White 1986). In general the highest depletion values are found for directions of the highest electron density. If we assume that ^7Li suffers the same depletion of K in the LMC as it does in the Galaxy we can use the results found for K to infer the present Li abundance in the LMC.

From the N(KI) reported in Vidal-Madjar et al (1987) we get $N(K)=3.5 \times 10^{12} cm^{-2}$ and $K/H=1.4 \times 10^{-9}$. Compared with the solar value for K it means that the combination of depletion and metal deficiency is 80. If we consider K depleted by a factor 15, as found above in the galaxy for a similar electron density, then K becomes deficient by -0.7 (in log), similar to the deficiency observed for C,N (-0.6) in the HII regions of the LMC, but slightly more deficient than O,S,Cl,Ar (-0.2,-0.3) (Dufour 1983). Constraining K to be deficient by at most a factor of 3 implies a depletion by a factor of 27. So to explain why so little K is observed in the LMC we have to choose between either an high deficiency of K in the LMC or an unconfortably high depletion.

The same situation translates to lithium. If K is depleted by a factor of 27 than also ^{7}Li should be depleted by the same amount and we have $^7Li/H<1.65x10^{-9}$ comparable with the value observed in the Milky Way. The other possibility is to have the ^{7}Li and K only slightly depleted. We know from the observed gas-to-reddening ratio that there is less dust in the LMC than in the Galaxy by about a factor of three. Thus we expect that in the grain-accretion hypothesis the general elemental depletion should be correspondingly reduced. If we adopt a factor 4 of depletion that is the average observed in the Galaxy we get $^7Li/H<2.6x10^{-10}$. this is very close to the minimum quantity of Li that can be synthetized in the Big Bang whatever the baryon density. There is not much room left for subsequent stellar ^{7}Li production.

In conclusion we argue that it is impossible to infer information on the primordial ^{7}Li value until the important question of Li depletion is solved. The knowledge of the K abundance in the LMC will give important information on this issue.

5.5 BORON AND BERYLLIUM IN THE LMC

For the galactic components the upper limits derived here are larger than what is generally obtained in the Galaxy and are not significant. In the LMC the hydrogen column density is one order larger than in the Galaxy and these are the first sensitive observations of these elements in an external galaxy.

Boron and beryllium have been proven to be mostly in the first ionization stage (Audouze et al 1973, Boesgaard 1985). The oscillator strengths are 1.1 for the BII 1362 lines (Praderie 1977), and are 0.338 for the stronger of the BeII 3130 A doublet (Boesgaard 1985). The upper limit of 15mA in correspondence of the boron line implies $N(B) < 8.3 \times 10^{11} cm^{-2}$ and $B/H < 3.2 \times 10^{-10}$. For Be the upper limit of 10mA implies $N(Be) < 3.4 \times 10^{11} cm^{-2}$ and $Be/H < 1.3 \times 10^{-10}$.

The boron upper limit is a bit less than the solar value of $4(+/-2) \times 10^{-10}$ found by Kohl et al (1977), but a bit larger than the generally assumed present day galactic value of 2×10^{-10}. The upper limit for Be is much less stringent being larger than the cosmic abundance of 2×10^{-11}.

As we have seen in chapter one boron and beryllium can be synthesized only by spallation processes and their present amount in the LMC is the result between the synthesis by spallation processes and destrucion by astration over the life of the Cloud. In our own galaxy the evolutionary abundance curve for beryllium shows a constant beryllium abundance at the solar value back in time to a corresponding metal deficiency of

-0.4. For boron the evolutionary abundance curve is not well specified by the observations (Reeves 1974) but it is reasonable to imagine a similar behaviour for the two elements. As it has been suggested by Reeves and Meyer (1978) the pattern shown by the evolutionary curve of Be point to an early rapid production followed by a substantial equilibrium by synthesis, astration and infall of primordial matter.

The present upper limits imply that the integrated amount of spallated nuclei in the Cloud has not been greater than in our own Galaxy.

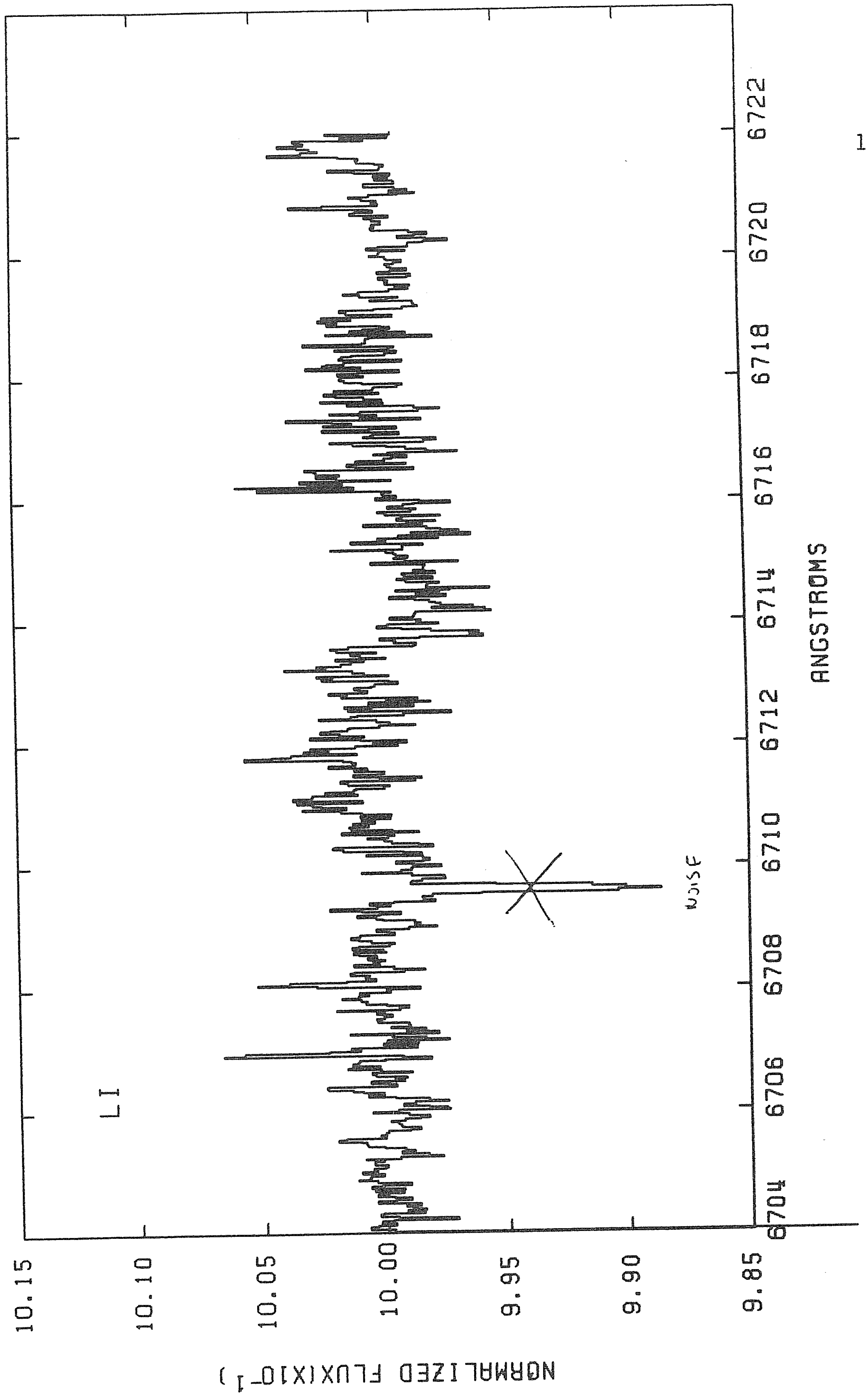


Fig 5.1 Spectrum of SN1987a in the Lithium region

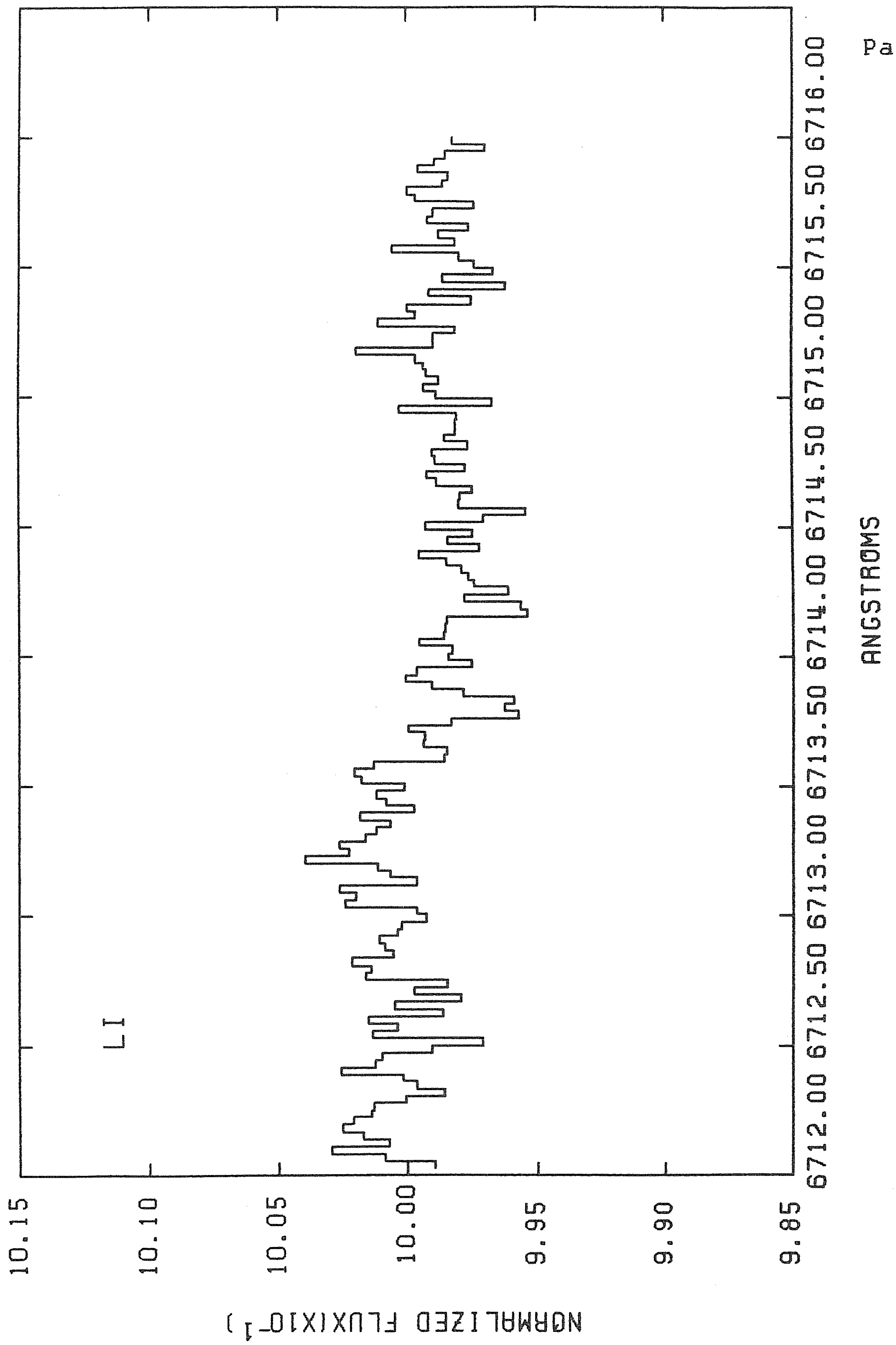


Fig 5.2 The spectrum of Fig 5.1 zoomed at the expected position for a lithium line originating in the LMC.

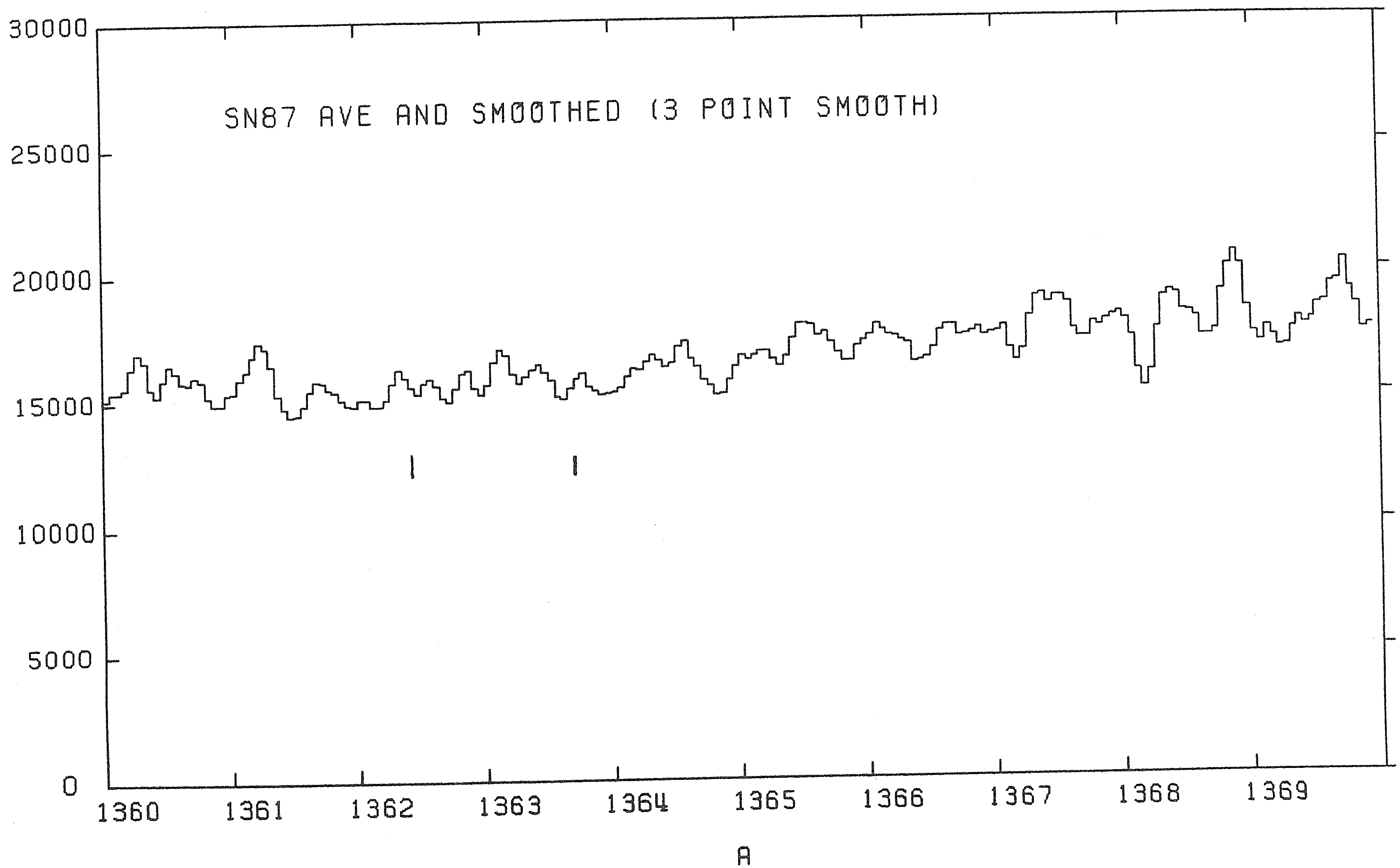


Fig 5.3 IUE spectrum of SN1987a around the Boron region

LITHIUM

	W(mA)	N(LiI)	ne	N(Li)	N(HI)	Li/H
GAL	<0.3	<1.0(8)	0.26	<1.65(11)	2.9(20)	<5.7(-10)
LMC	<0.3	<1.0(8)	0.24	<1.65(11)	2.6(21)	<6.3(-11)

BORON

	W(mA)	N(BII)	N(B)	N(H)	Be/H
LMC	<15	<8.3(11)	<8.3(11)	2.6(21)	<2(-10)

BERYLLIUM

	W(mA)	N(BeII)	N(Be)	N(H)	Be/H
LMC	<10	<3.4(11)	<3.4(11)	2.6(21)	<1.3(10)

Table 5.1 Summary of the quantities derived for lithium, beryllium and boron.

CONCLUSIONS

The main conclusions of this investigation are the following:

1) We have considerably extended the number of lithium measurements in Population II stars. The new sample shows wider physical properties among the components and is therefore is representative. The metallicity range extends down -3.5, the range of effective temperatures reaches 6350 K and there are few stars with radial velocities exceding 350 Km/sec. The uniformity of the lithium abundance is confirmed. For stars with [Fe/H]<-1.4 and surface temperatures between 5500 K and 6300 K we found an average log N(Li)=2.08(+/-0.10), which tends to reach 2.2 as Teff approaches 6300 K. We argue that the warmer stars offer more reliable measurements of the primordial lithium or a better lower limit than the average of all the population II stars. According to the new computation for the cosmological lithium synthesis recently provided by Kajino et al (1987) and to the value of Li/H=1.6(+/-0.25)x10^{-10} provided by the 11 stars with Teff>5900 K and [Fe/H]<-1.2, two ranges of baryon-to-photon numbers can be distinguished. Only the low values range is consistent with the recent measurements of primordial helium by Pagel (1987) implying that the baryon-to-photon number is lower than <2.3x10^{-10}. This corresponds to OMEGA< $0.009h_o^{-2}$ significantly smaller than

previously quoted limits.

2) We have undertaken the first investigation with the aim of establishing the beryllium abundances in metal-deficient stars. So far, we have observed 8 stars. In four stars, those with metallicities below -1.5 we set an upper limit on Be abundance of 2.5×10^{-12} (for HD140283 less than 3×10^{-12}).
In three of the other stars, those with -1.3<[Fe/H]<-1, we claim a marginal detection of beryllium in 1×10^{-12} - 2.5×10^{-12} range and in one, HD 76932, an upper limit of 3×10^{-12}. Our results and the literature show that beryllium abundance never exeeded the present solar value ruling out models for galactic evolution which entail an early burst of Be production. These results have been used to predict the abundances of the other spallogenic nuclei such as ^{7}Li, ^{6}Li and $^{10,11}0B$. It has been shown that an upper limit of 0.1dex can be set to the fraction of the lithium in Population II stars which is either non-primordial, or due to spectral blending with ^{6}Li, classifying virtually all of the measured 7Li as primordial.

3) Fully aware of the importance of B observations in cool stars we have made the first search for BI 2496 lines in IUE spectra of the brightest population II stars. No evidence of BI resonance lines has been found so far. In HD 140283 we have set an upper limit of < 2×10^{-11}, i.e. 40 times less than the solar value of $4(+/-2) \times 10^{-10}$. This is the first measurement of B abundance in a population II star and, with the ecxeption of the sun, the only one performed on a solar type star. For HD 76932, a preliminary analysis gives a B abundance of $B/H < 2 \times 10^{-10}$, i.e. less than the present "cosmic" value. The

presence of an unidentified line, not resolved with IUE, prevents B analysis in HD 216385 ([Fe/H]=-0.6) and cool stars with similar or greater metallicity unless higher spectral resolution is available. In agreement with the Be observations these results provide evidence that spallation processes were unable to produce significant quantities of boron at the beginning of the Galaxy. In particular, the production of the lithium observed in the Population II stars cannot be ascribed to spallation processes induced by a still hypothetical component of low-energy cosmic rays (<10 MeV).

4) Spectra of the SN1987A, taken during the first days following the explosion with the ESO CAT+CES+Reticon at La Silla and with the IUE in the high resolution mode, are analyzed in a search for interstellar 6707 LiI, 3130 BeII and BII resonance lines. No evidence for any ion either at the Galactic component or at the expected position of the Large Magellanic Cloud has been. For LiI the minimum detectable equivalent width is 0.3 mA corresponding to N(LiI)< 6.7 10^{8} cm^{-2}. The total N(Li) in the gaseous form is estimated at less than $1.65 x 10^{11} cm-2$ when the ionization fraction is taken into account using the CaI and CaII observations. This correspond to a Li/H of less than $6.3x10^{-11}$ towards SN1987a. When compared with the N(KI) this very low value necessarily implies considerable depletion of both these elements. We argue that the present $^{7}Li/H$ abundance can be as high as $2x10^{-9}$ comparable to the Galactic abundance. For B the minimum W is 15 mA and N(B)<8.3 $10^{11} cm-2$ and $B/H<3.2x10^{-10}$, i.e. it is less than the solar value. This result indicates that the spallation processes in the LMC have not been greater than in the Galaxy.

ACKNOWLEDGEMENTS

A very special thank to prof. Dennis Sciama who introduced me to these topics offering his unfailing encouragement and support.

I would also like to thank John Beckman, Giovanni Vladilo, Rafael Rebolo and Fiorella Castelli whose contributions to this work have been invaluable.

Among the several people with whom I have had fruitful and stimulating discussions, I would like to thank particularly Monique and Francois Spite, Hubert Reeves, Bernard Pagel and Ann Merchant Boesgaard.

REFERENCES

Abia, C. and Canal, I.:1987, Astron. Astrophys. in press.

Aller, L.H., and Greenstein,J.L.: 1960 Astrophys. J. Suppl. 5,139.

Arribas, S., Martinez-Roger, C.: 1987, Astron. Astrophy. in press.

Audouze, J., Lequeux, J. and reeves, H.: 1973, Astron. Astrophys. 28, 85.

Audouze, J. and Reeves, H.:1982, in "Essays in Nuclear Astrophysics" ed. by C.A. Barnes, D.D. Clayton and D.N. Schramm, 355.

Audouze, J.: 1986, in "Nucleosynthesis and chemical evolution" proceedings of the 16th advanced Course Swiss Society of Astrophysics and Astronomy.

Audouze,J., and Tinsley, B.M.: 1974, Asdtrophys. J. 192,487.

Audouze, J., Boulade, O., Malinie, G., Poilane, Y.: 1983, Astron. Astrophys. 127, 164.

Baade and Magain: 1987, ESO Workshop on SN1987

Baldwin, J., Boksenberg, A., Burbidge, G., Carswell, R., Cowsik, R., Perry, J. and Wolfe, A.,: 1977, Astron. Astrophys. 61, 165.

Barbuy, B.: 1978, Astron. Astrophys. 67,339.

Barbuy, B., Spite, M. Spite, F: 1985, Astron. Astrophys. 144,343.

Barker, F.C.:1972 Astropys.J 173, 477.

Baschek, B.: 1959, Z Astrophys. 48,95.

Beaudet, G., and reeves, H.: 1984, Astron. Astrophys. 134, 243.

Beckman, J.E., Rebolo, R., Molaro P.:1986, Proc. Second IAP

Rencontre on nuclear astrophysics, 29.

Beers, T.C., Preston, G.W., Shectman, S.A.: 1985, Astron. J. 90, 2089.

Bidelman, W.P. MacConnell, D.J.: 1973, Astron. J. 78, 687.

Black, J.: 1975, Ph.D. thesis, Harvard University.

Black, J.: 1987, private comunication to White (1986)

Bodenheimer, P.: 1966 Astrophys. J. 144, 103.

Boesgaard A.M.,: 1974, Astron. Astrophys. 34, 9.

Boesgaard, A.M.:1976, Astrophys. J. 210,266.

Boesgaard, A.M., Heacox, W.D., Conti, P.S.: 1977, Astrophys. J. 214,124.

Boesgaard, A.M. and Heacox, W. D.: 1978, Astrophys. J. 226,888.

Boesgaard, A. M., and Praderie F.: 1981 Astrophys. J. 245,219.

Boesgaard, A. and Steigman, G.:1985, Ann. Rev. Astron. Astrophys. 23,319.

Boesgaard, A.M.: 1985, P.A.S.P. 97,984.

Boesgaard, A.M.,: 1985, Publ. Astron. Soc. Pac. 97, 37.

Boesgaard, A. M., Tripicco, M. J.: 1986, Astrophys. J. 302, L49.

Boesgaard, A. M., Tripicco, M. J.: 1986b, Astrophys. J. 303, 724.

Boesgaard, A. M.: 1987, 321 ?.

Boesgaard, A. M., Budge K. G., Burck, E. E.: 1988 Astrophys. J. Febb. issue.

Bohlin, R.C., Savage, B.D., Drake, J.F.: 1978, Astrophys. J. 224, 132.

Boksenberg, A.: 1972, Proceedings of the ESO/CERN "Conference on Auxiliary Instrumentation for Large Telescopes", Geneve 1972, 295.

Bond, H.E.: 1970, Astrophys. J. Suppl. Ser. 22, 117.

Burbidge E.M., Burbidge G.R., Fowler W.A. and Hoyle F.: 1957,Rev. Mod. Phys., 29, 547.

Busek, P. R.: 1971, in "Theoretical abundances in meteorites" Ed. B. Masson, Gordon and Braech, New York.

Cacciari, C., Malagnini, M.L., Morossi, C., Rossi, L.,:1986 preprint.

Cayrel R., Cayrel de Strobel, G., Campbell, B., Dappen, W.: 1984, Astrophys. J. 283,205.

Cayrel de Strobel, G., Bentonilla, C., Hauck, B., Dunquennoy, a.: 1985, Astron. Astrophys. Suppl. Ser. 59, 145.

Cayrel R.:1986, Astron. Astropys. 168, 81.

Cardelli, J., Bohm-Vitense, E.: 1982, Astrophys. J. 262, 213.

Cameron, A.G.W., Colgate, S.A., Grossman: 1973, Nature 243204.

Carney, B.W., Peterson, R.C.: 1981, Astrophys. J. 245,238.

Carney, B.W.: 1979, Astron. J. 233, 211.

Carney, B.W.: 1983, Astron. J. 88, 623.

Castelli, F.: 1985, "A procedure to compute a stellar synthetic spectrum" Publ. OAT 984

Caughlan, G.R., Fowler, W.A., Harris, M.J., and Zimmerman, B.A.:1985, Atomic Data Nucl. Data Tables, 22, 197.

Caves, T.C., and Dalgarno, A.: 1972, J. Quant. Spectrosc. Rad. Transf, 12, 1539.

Chaffee, F.H., and Lutz, B.L.: 1977, Astrophys. J. 213, 394.

Chamberlain, J., and Aller,L.H.: 1951 Astrophys. J. 114,52

Chmielewski, Y., Muller, E.A., Brault, J.W.: 1975, Astron. astrophys. 42, 37.

Clegg, R.E.S.: 1977, M>N>A>S> 181,1.

Cohen, J.G., and Strom, S.E.: 1968, Astrophys. J. 151,623.

Curtis, D., Gladney, E., and Jurney E.: 1980, Geochim. Cosmochim. Acta, 1945.

De Boer, K. S., Savage, B.D.: 1980, Astrophys. J. 238,86.

Duncan, D. K., Jones, B.F.: 1983, Astrophys. J. 271, 663.

Eggen, O.J.: 1969, P.A.S.P. 81, 553.

Eggen, O.J.: 1973, Astrophys. J 182, 821.

Eggen, O.J.: 1979, Astrophys. J 229, 158.

Ferlet, R., and Dennefield, M.: 1984, Astron. Astrophys. 138, 303.

Field, G.B. 1974, Astropys. J. 187, 453.

Fowler, W.A., caughlan, G.R., Zimmerman, B.A.: 1975. Ann. Rev. Astron. Astrophys. 13,69.

Grabowski, B.: 1976, Acta Astronomica 26,147.

Greenstein, J., L. Tandberg-Hanssen, E.: 1954, Astrophys. J. 119,113.

Griffin, R.,: 1985, Astron and Astrophys. 149,437.

D'Antona, F., Mazzitelli, I.: 1984, 138, 431.

Dappen 1984, private comunication referred in Spite and Spite 1982.

Dufour R. J.: 1983, IAU Symp. 108, 353.

Gerbaldi, M. Faraggiana, R., Molaro, P.: 1986 proc. IUE conference ,49..

Duncan, D. K., Jones, B. F.: 1983, Astrophys. J. 271,663.

Gustafsson, B., Bell, R.A., Eriksson, K., Nordlund, A.: 1975, Astron. Astropys. 42, 407.

Hall, D.N.B., and Engvold, O. :1975 Astrophys. J. 197,513.

Herbig G. H.: 1968, Zs. f. Ap. 68, 243.

Hernshaw, J. B.: 1976, Astron. Astrophy. 51, 71.

Hobbs, L. M.: 1984, Astrophys. J. 286, 252.

Hobbs, L.M., and Duncan, D.K.: 1987, Astrophys. J. in press.

Hobbs, L. M., Pilachowski, C.A. :1986, Astrophys. J. 309, L17.

Johnson, H.L.: 1966, ann. Rev. Astron. Astrophys. 4, 193.

Kajino, T., Toki, H. and Austin S. M.: Astrophys. J. 319, 531.

Kawano, L., Schramm D. and steigman G.: 1987, Astrophys. J. in press.

Kohl, J. L., Parkinson W. H., Withbroe G.L.: 1977 Astropys. J. 212, L101.

Kurucz R.L. and Peytremann E.: 1975, Smithsonian Ap. Obs. Spec. Rept., No 391.

Kurucz, R.L.:1979 Astrophys. J. Suppl 40,1

Kurucz, R.L: 1981 Smithsonian Astrophysical Observatory Special report No. 390.

Kurucz R.L. and Avrett H. E.: 1981, Smithsonian Astrophysical Observatory Special report No. 391.

Laird, J.B., Carney B.W., Latham D.W., Kurucz R.L.:1986 "Stellar Populations" M.Tosi and C. Norman editors, preprint No. 130, Space Telescope.

Magain, P.: 1984, Astron. Astrophys. 132,208.

Magain, P.: 1987, "El mensajero", 47, 18.

Maurice, E., Spite, F., Spite, M.: 1984 Astron. Astrophys. 132,278.

McEachran,R. P., and Cohen M.: 1982, J. Quant, Spectroscop. Radiat. Transfer 27,111.

Meneguzzi M., and York D. G.: 1980, Astrophys. J. 235, L111.

Meneguzzi M., Audouze, J., Reeves H. : 1971, Astron. Astrophys. 15, 337.

Mihalas, D. 1970, "Stellar atmospheres", 163.

Michaud, G., Fontaine, G., Beaudet, G.: 1984, Astrophys. J. 282, 206.

Mitler , H. E.: 1972, Ap. and Space Sci., 17, 186.

Molaro,P., and Beckman J.E.:1984 Astron. Astrophys. 139, 394.

Molaro, P., Beckman J.E., and Castelli, F.:1984, Proc. 4th European IUE Conference, ESA SP-218, 197.

Moore C.E., Minnaert, M.G.J., Houtgast, J.: 1966, NBS monograph 61.

Morton, D.C, Smith, A.M. and Stecher, T. P. 1974, Astrophys. J. 189, L109.

Morton. D.C. 1975, Astrophys.J., 197,85.

Morton, D.C.: 1978, Astrophys. J. 222, 863.

Norgaard, H., and Fricke, K.J.: 1976 Astron and Astrophys. 49,337.

Olive, K.A., Schramm D.N., Steigman G., Turner M.S., and Yang J.: 1981, Astropys. J. 246

Pagel,B.: 1987 in "Advances in Nuclear Astrophysics", edited by Vangioni-Flam, J. Audouze M. Casse`, J-P Chieze and J. Tran Thanh Van, 53.

Patenaude, M.:1978, Astron. Astrophys. 66, 239.

Peebles P.J.E., 1966, Phys. Rev. letters, 16, 410.

Peterson,R.C., and Carney, B.W.: 1979, Astrophys.J. 231,762.

Peterson,R.C., :1980, Astrophys.J. 235,491.

Peterson,R.C.: 1981, Astrophys.J. 244,989.

Praderie F., Boesgaard A.M., Millard, B., and Pitois M.L.: 1977, Astropys. J. 214, 130.

Quirk, W.J., and Tinsley, B.M.: 1973 Ap.J. 179,69

Rebolo, R., Beckman J.E., Molaro,P.:1987 Astron. and Astrophys Letters in press.

Reeves, H,, Fowler, W.A., Hoyle F.: 1970, Nature 226, 727.

Reeves,H.: 1974, Ann Rev Astron. Astrophy. 12, 437.

Reeves, H, and Meyer, S.P.,: 1978, Astrophys.J. 179, 343.

Relyea, L.J., Kurucz, R.L.: 1978, Astrophys. J. Suppl. ser. 37,45.

Ryter, C., Reeves, H., Gradssztajn, E., and Audouze, J.: 1970, Astron. Astrophys. 8, 389.

Roberts, J.R., Andersen, T., Sorensen, G.: 1973, Astrophys. J. 181, 587.

Rolfs, C. and Kavanaugh, R.W., :1986, Nucl. Phys. A455, 179.

Ross, J.E., and Aller, L.H.: 1974, Solar Phys. 36, 11.

Saio, H., Yoshii, Y.: 1979, PASP, 91, 553

Sadakane, K., Jugaku, J. and Masahide Tkada-Hidai: 1985, Astrophys. J. 297,240.

Sandage A., 1969, Astrophys. J. 158, 115.

Sandage A., Fouts, G.: 1987, Astron. J. 92, 74.

Schroder,U., redder, A., Rolfs, C., Azuma, R.E. Buchmann, L., Campbell, C., King, J.D. and Donoghue, T.R., 1986. preprint.

Snell R.L., Vanden Bout, P.A.,: 1981, Astrophys. J. 250, 160.

Sneden, C.: 1974, astrophys. J. 189, 493.

Sneden, C. and Bond , H.E. : 1976, astrophys. J. 204, 810.

Snow, T. P.: 1975, Astropys. J. 202, L87.

Snow, T.P., Weiler, E. J. and Oegerle, W. R.: 1979, Astrophys. J. 234, 506

Spite,F. and Spite, M. : 1978, Astron Astrophys. 67,23.

Spite,F. and Spite, M.: 1980, Astron. Astrophys. 89,118.

Spite,F. and Spite, M.: 1982, Astron. Astrophys. 115,357.

Spite,M., Maillard, J.P., and Spite, F: 1984, Astron. Astrophys. 141, 56.

Spite,F. and Spite, M.: 1986, Astron. Astrophys. 163,140.

Spite,F. and Spite, M., Peterson, R.C., Chaffee, F.M.: 1987, Astron. Astropys. 172, L9.

Steenbock,W., Holweger, H.: 1984, Astron. Astrophys. 130, 319.

Tomkin, J., Sneden, C., Lambert, D. L> :1986, Astrophys. J. 302, 415.

Traub,W.A., and Carleton, N.P.:1973, Astrophys. J. 184, L9.

Truran,J.W., Cameron A.G.W. : 1971, Astrophys. Space Sci. 14,179.

Vanden Bout, P.A., Snell, R.L., Vogt, S.S. and Tull, R. G.: 1978, Astrophys. J. 221, 598.

Vidal-Madjar, A., Andreani, P., Cristiani, S., Ferlet, R., Lanz, T. and G. Vladilo: 1987, Astron. Astrophys.

Wagoner, R.V., Fowler W.A. and Hoyle F., 1967, Astrophys. J. 148,3.

Wagoner,R.V.: 1969, Astrophys. J. Suppl. 18,247.

Wagoner,R.V.: 1973, Astrophys. J. 179, 343.

Wallerstein, G. (1962) Astrophys. J. Suppl. 6,407.

Wallerstein, G., Conti, P.S. :1969, Annual Rev. Astron. Astrophys. 7,99.

Wayte 1987 personal comunication

Walker, T.P., Mathews, G. J., and Viola V. E. :1985 Astrophys.J 299,745.

Weller M.R., Furst, M., Tombrello, T. A., and Burnett D.S.:1977

Astrophys.J. 214,L39.

Wiese, W.L.,and Martin, G. A.: 1980, Wavelengths and Transition Probabilities for Atoms and Atomic Ions, Part 2 (NSRDS-NBS 68), 359.

Withbroe 1971

White, R.E.: 1986, Astrophys. J 307, 777.

Zappala, R. R.: 1972, Astrophys. J %72, 57.

Yang J., Schramm D.N., Steigman G. and Rood R. T.: 1979, Astropys. J. 227,697.

Yang J., Turner M.S., Steigman G., Schramm D.N., and Olive K.A.: 1984, Astropys. J. 281, 493.

York, D.G., Meneguzzi, M. and Snow, T.P.: 1982, Astrophys. J. 255, 524.