TRENDS OF ELEMENT ABUNDANCES IN THE STARS OF OUR GALAXY

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ABSTRACT. The analyses of element abundances in a variety of stars, formed at different times in our Galaxy, are presented in an effort to determine the distribution of elemental abundances at various stages in the evolution of the Galaxy.

1. Introduction. The different populations in the solar vicinity.

Our Sun is located in the external part of the disk of our Galaxy. Different investigations based on star counts (cf. in particular: Gilmore and Reid (1982), Gilmore and Wyse (1985), Sandage(1987) Gilmore et al. (1989))have shown that, in a cylinder perpendicular to the galactic plane above the Sun, it is possible to disentangle up to four different Populations: the halo , and the disk which is now divided in three different subsystems: the old thick disk, the old thin disk, and the young thin disk where star formation still occur.

Recently Burkert Truran and Hensler (1991) have proposed a chemodynamic model of the collapse of our Galaxy. They show with a minimum of hypotheses, that the gas collapsed into the equatorial plane in succeeding steps: when the gas collapses indeed, the star formation rate increases and provides sufficient energy to stop the free fall collapse. Later, when star formation slows down, due for example to the lack of gas, the collapse restarts. The different populations correspond to the different steps of this collapse. First the halo collapses on a rapid time scale (10^9years) in a "thick disk". During about another 10^9years stars are formed inside this "thick disk". Then it collapses into an "old thin disk" and during about 5×10^9 years stars are formed inside, and finally the old thin disk itself collapses into the young thin disk feature.

Moreover, if the material in the Galaxy, at each step of its formation, has been well mixed, a correlation between metallicity and age is expected . For example it can be admitted that all stars with [Fe/H]<-1 dex belong to the halo. The characteristics of the different subsystems are summarised in Table 1.

Since the Galactic plan belongs to all the subsystems, it is possible to find in this Galactic plane, stars formed at different steps of the life of the Galaxy. In the solar vicinity, these stars are close to us: it is possible to analyse in detail their chemical composition as a function of metallicity for a better understanding of the processes which determine the chemical evolution of the galaxies.

In section 2, recent spectroscopic studies of detailed abundance patterns in field Galactic stars located in the solar neighborhood (less than about 100pc from the Sun) are presented as a function of metallicity. In section 3 the composition trends in the field stars and in the cluster stars are compared.

B. Barbuy and A. Renzini (eds.), The Stellar Populations of Galaxies, 123–132.

Table 1. The different Populations in the Galaxy

	scale height (pc) (pc)	time scale of formation (years)	age of the stars* (years)	metallicity
galactic halo	3200	$>10^9$	15×10^9	[Fe/H]<-1.0
galactic disk				
thick disk	1000	0.5×10^9	14×10^9	−1<[Fe/H]<−0.5
old thin disk	270	5×10^9	14×10^9 to 9×10^9	−0.5<[Fe/H]<−0.3
young thin disk	50	...	$<9\times10^9$	[Fe/H]>−0.3

*Approximate values of the ages are determined assuming that the age of the halo stars is $\approx15\times10^9$years.

2- Composition trends in field stars

There have been several reviews of stellar abundance trends in recent years in articular Spite and Spite (1985), Gustafsson (1987), Lambert(1989), Wheeler et. al. (1989), Nissen, P.E.(1990), and recently a very interesting paper from Ryan et al. (1991) who observed extremely metal poor stars (eight of them with [Fe/H]<–3), but with a rather low S/N ratio. We will discuss here only some elements for which new measurements have been recently obtained.

2-1 THE VERY LIGHT ELEMENTS: Li, Be

These elements are very peculiar since they cannot be formed inside supernovae neither in normal hydrostatic nor explosive conditions: lithium and beryllium are formed by cosmic ray spallation (Meneguzzi et al. 1971), ^{7}Li (but not ^{9}Be) can be formed during the standard Big-Bang (SBB). Other possible sources of lithium are the novae, the red giants, and perhaps, the very massive stars.

The lithium abundance in stars of different populations has been extensively studied by different groups.In a main sequence star, lithium is destroyed as soon as the convective zone reaches the layers where the temperature is larger than 2×10^6K, but in the very young disk stars which have had no time to destroy their lithium, log N(Li)≈3 and log N(Be)≈1.3 (for log N(H)=12).

In the oldest halo dwarfs of our Galaxy the abundance of lithium is lower: log N(Li)=2.1±0.1 (Spite and Spite 1982, Spite et al. 1987, Rebolo et al. 1987, Hobbs and Pilachowski 1988, Hobbs & Thorburn 1991). In a large interval of metallicity -3<[Fe/H]<-1.2 there is NO correlation between lithium abundance and metallicity (Fig.1). Moreover it seems that the variation of the lithium abundance from star to star is within the error bars

The standard Big Bang produces a very small amount of Be. The observed beryllium is probably built by spallation (action of cosmic rays on CNO elements). In Fig.1 the abundance of beryllium is seen to track the iron abundance; the data are taken from Ryan et al. (1990), Gilmore et al. (1991) and Boesgaard (1990). It can be seen that, in the oldest stars, the abundance of beryllium is very low and, as a consequence the spallation processes has not been very efficient, not efficient enough to build a significant amount of lithium.

The constant lithium abundance (independent of metallicity and mass) in the halo stars, provides the primary basis for the view that the surface lithium found today in the halo dwarfs constitutes the nearly unaltered lithium fraction produced by the Big-bang. It must be clear however,that this is not a proof. Nevertheless, if we assume it, a consequence is that an important formation of lithium occured later in our Galaxy. The possible sites of this production could be the AGB phase of the intermediate mass red giants (Smith & Lambert 1990) and the novae (D'Antona & Matteucci 1991).

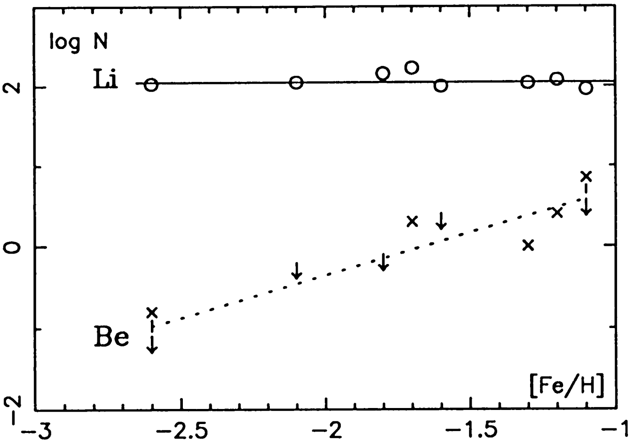

Fig.1 The abundances of both beryllium and lithium has been measured for 8 hot halo dwarfs. For these stars log N(Li) (open circles) and log N(Be) (crosses, or arrows for upper limits) have been plotted versus [Fe/H]. It can be seen that the abundance of lithium is independent of the metallicity and that, on the contrary, the abundance of beryllium seems to track the iron deficiency.

2-2 THE CNO GROUP.

These elements are of particular significance since after hydrogen and helium they are the most abundant elements in the Universe.

Carbon: The abundance of carbon in the atmosphere of a star may be altered at various stages of stellar evolution and especially at the red giant phase (dredge-ups of CN cycle fusion). Therefore in order to ascertain the trend of C/Fe as a function of metallicity, it is particularly important to concentrate on dwarf stars.

Laird (1985) has not observed any variation in [C/Fe] with metallicity,but Tomkin et al.(1986) and Carbon et al.(1987) asserted that a trend of increasing [C/Fe] ratios with decreasing metallicity existed. Wheeler et al.(1989) compiled all these data, trying to correct some systematic errors of the analyses. In this way the overall trend toward larger C/Fe ratio in the halo becomes more obvious . However, for most of these stars, the oxygen abundance is unknown, and the trend in [C/Fe] is affected by the unknown fraction of C combined in the CO molecule, and thus very dependent on the oxygen abundance assumptions. Ryan et al.(1991) measured the carbon abundance in 3 dwarfs with [Fe/H]<2.6, their data are consistent with the previous works and mildly support a larger value of C/Fe in the halo.

Oxygen: The trend of [O/Fe] with [Fe/H] can provide a check of the time scale of the formation of the Galaxy. The creation site of oxygen indeed, is restricted to very massive stars which have a very short life time; in contrast, iron can be created also during the evolution of lower mass stars which have a life time which spans the time of the Galaxy formation. Only the very massive stars had time to enrich the material which formed the halo stars.

All surveys of the oxygen abundances concluded that, in the thick disk and the halo, oxygen is overabundant relative to iron: cf. Clegg et.al (1981), Gratton and Ortolani (1986), Barbuy (1988), Magain (1988), Barbuy and Erderlyi-Mendes (1989), Abia and Rebolo (1989), Sneden et al. (1990). In the disk, the oxygen-to-iron ratio decreases slowly when [Fe/H] increases to reach the solar value. However the abundance values depend (Figure 2) on the type of oxygen lines used (forbidden, permitted, or lines of the OH molecule) and some more work has to be done in order to achieve a good agreement. Following Barbuy and Erderlyi-Mendes, [O/Fe] deduced from the forbidden lines, is about +0.4 dex in the halo; it is more than +1.0 dex following Abia and Rebolo who used the permitted triplet. Recently we could observe at the CFH telescope with a resolution of 80000, and a very high S/N ratio, the forbidden line at 630nm in some of the stars observed by Abia and Rebolo. We found a systematic difference of about 0.5 dex between the abundances deduced from the permitted lines by Abia and Rebolo and the abundances we deduced from the forbidden line with the same atmospheric model (Spite & Spite 1991). A similar difference had been found by Magain (1988) on one dwarf HD76932.

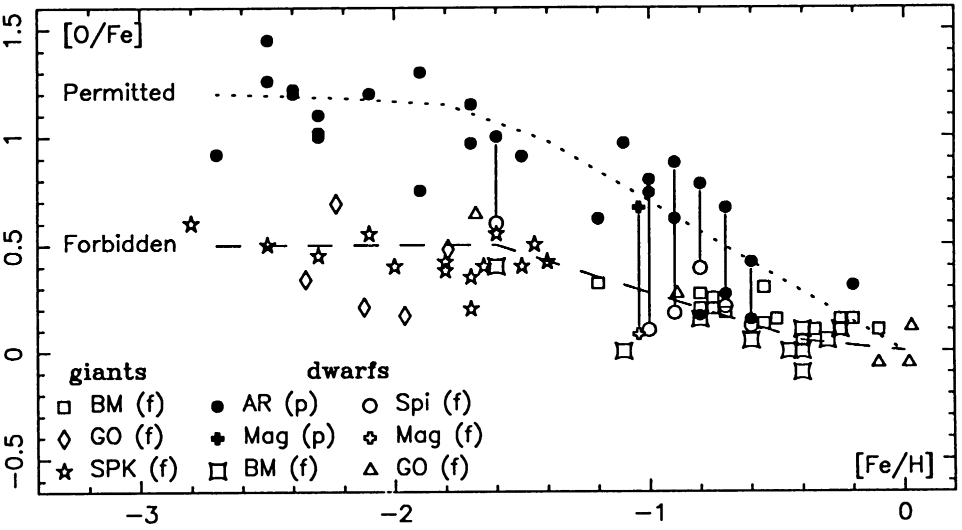

Fig.2 [O/Fe] versus [Fe/H] following Barbuy 1988 and Barbuy & Erderlyi-Mendes 1989 (BM), Gratton & Ortolani 1986 (GO), Abia & Rebolo 1989 (AR), Magain 1988 (Mag), Sneden et al. 1990 (SKP) and Spite & Spite (Spi). It seems that there is no systematic difference between dwarfs and giants but a systematic difference between the measurements based on the permitted lines and those based on the forbidden lines. (When the two systems have been measured in the same star the two measurements are joined by a straight line.)

It has been shown that the permitted lines are sensitive to non-LTE-effects. Recently Kiselman (1991) has studied the Non-LTE effects on oxygen abundance determinations; the correction computed for the permitted lines at 777nm, does not exceed 0.3dex. As a conclusion we would say that the overabundance of oxygen in halo stars is about +0.4dex, and that the large discrepancy between the permitted and the forbidden lines remains partly unexplained.

2-3 THE LIGHT METALS FROM Na to Ca (11 $\leq$ Z $\leq$ 14)

From the nucleosynthesis theory, these elements are formed in the same nucleosynthesis process but the formation rate of the odd light metals relative to the even metals can depend on the metallicity of the supernova. It is thus usual to consider the group of the odd Z elements (Na, Al) and to compare their abundance to the group of the even Z elements like Mg or Si.

The even Z elements: All recent studies of these elements have yielded similar results. The even Z elements are overabundant in the halo relative to iron: for exemple [Mg/Fe]≈+0.4dex up to [Fe/H]≈−3. In the disk, this ratio decreases slowly to reach the solar value. (Laird 1986, François, 1986a, 1987, 1988, Magain 1987, 1989, Gratton & Sneden 1987, 1988, 1991, Ryan et al. 1991). Following Molaro & Castelli (1990) and Molaro & Bonifacio (1990), the ratio [Mg/Fe] increases slowly in the extreme halo stars ([Fe/H]<-3). The mean behavior of [Mg/Fe] as a function of [Fe/H] is displayed in fig.3.

Similar enhancement of the ratio [M/Fe] in the halo are obtained for sulfur, and silicon (François, 1988, Gratton and Sneden 1991) , but Peterson *et al.* (1990) suspect a tendency for this enhancement to decrease with the increasing atomic number Z.

The odd Z elements: Aluminum and sodium are represented by only few unblended lines in the stellar spectra, and probably for this reason, the general trend of their abundances is up to now not completely clear.

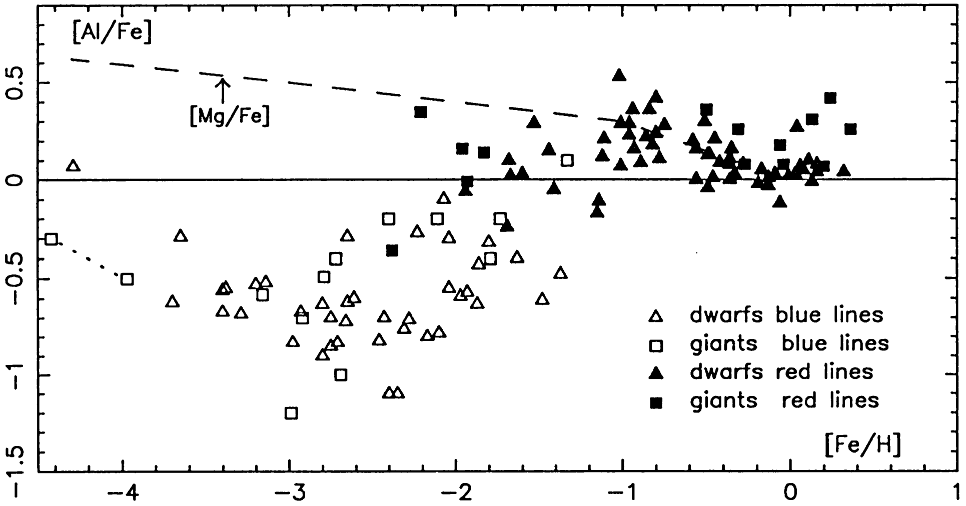

Fig.3 [Al/Fe] versus [Fe/H] for dwarf and giant stars. The filled symbols represent the aluminum abundance deduced from the "red" lines and the open ones, the abundance deduced from the "blue" resonance lines. In the region of the figure where blue or red lines have been used (-2.4>[Fe/H]>-1.3) it seems that there is a systematic difference between the two sets of measurements.
As a comparison, the dotted line represents the mean behavior of [Mg/Fe] versus [Fe/H].

-Na:

[Na/Fe] is constant up to [Fe/H]=-4.4: [Na/Fe]≈0 according Gratton and Sneden (1988), Peterson et al. (1990), and Molaro and Bonifacio (1990), who used the resonance sodium lines and [Na/Fe]}≈-0.2 according François (1986b) who used weak lines at about λ≈ 616nm.

-Al:

To determine the abundance of aluminum, sometimes the "red" lines at λ 699.6nm and sometimes the "blue" resonance lines at λ 394.4nm are used (cf. François, 1986a, Magain 1987, Gratton & Sneden, 1988, Molaro & Bonifacio 1990, Ryan et al. 1991).

Clearly, the "blue" lines are used only if the metallicity of the star is so weak that the "red" lines disappear. Figure 3 shows the ratio [Al/Fe] as a function of [Fe/H] as computed by different authors. From the "red" lines: [Al/Fe] is almost constant. However, as soon as the "blue" aluminum lines are used the picture changes completely. It is apparent from Figure 3 that in the range -2.2<[Fe/H]<-1.4, the mean value of [Al/Fe] is found to be +0.1 if the "red" lines are used and -0.4 if the "blue" lines are used. To check this effect, it would be very interesting to measure the "blue" and the "red" lines in the same stars.

The odd-even effect Since Mg, Al and Na are supposed to be built in the same nuclear process, it is usual to compare directly the ratios [Al/Mg] or [Na/Mg] with [Mg/H] or [Fe/H]. The ratios [Na/Mg] and [Al/Mg] are independent of the metallicity in the disk, then these ratios decline with decreasing metallicity.

We should expect that when sodium and aluminum are directly compared to magnesium the scatter decreases, but this is not the case. It is likely that this scatter is mainly attributable to measurement errors as suggested in figure 3.

2-4 THE IRON PEAK ELEMENTS FROM Ca TO Ni ($20 \leq Z \leq 28$)

These elements are mainly produced by explosive Si burning during supernovae explosions. Recent nucleosynthesis models predict that the odd elements of the Fe group might have been underproduced in the massive supernovae which alone were able to enrich the material during the halo phase. The poor knowledge of the hyperfine structure which affects the lines of odd elements of the Fe group and the lack of reliable oscillator strengths for the relevant transitions explain that few reliable data existed. Recently Sneden and Crooker (1988), Gratton (1989), Peterson et al. (1990) and Gratton & Sneden (1991) have observed a sample of metal poor stars for a precise analysis of the relative abundances of these different elements, studying the best accessible transitions of these elements from high resolution high S/N spectra. Their results are summarized in fig.4 where are compared the pattern of these elements in the halo and in the disk.

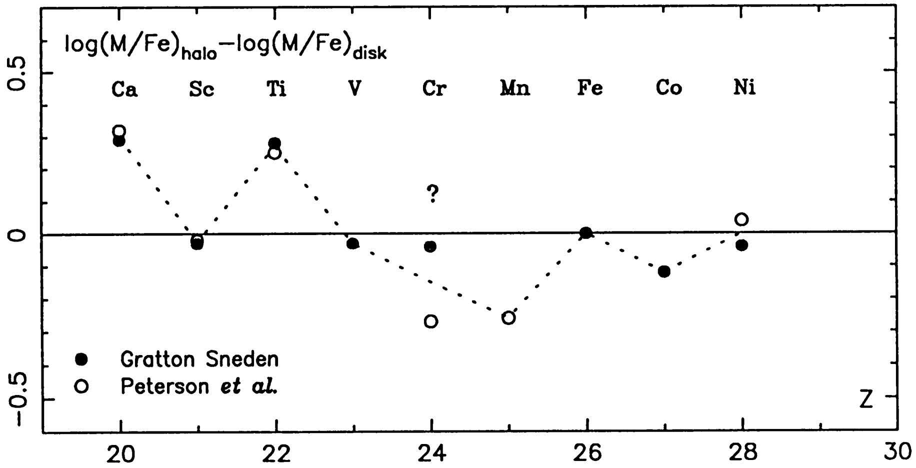

Fig.4 Difference between the relative abundances in the halo and in the disk stars for the iron peak elements. The abscissa is the atomic number Z.

Let us note that the overabundance of Scandium and Nickel found by Magain & Zhao (1989) and Luck & Bond (1983,1985) in the halo stars, has not been confirmed.

2-5 THE RARE EARTHS

The elements heavier than iron are synthesized by neutron capture reactions, in either the r (rapid) or the s (slow) process. From the measurements of the abundances of the different isotopes in the solar system we know for example that Ba and Sr, in the Sun, have been mainly formed by the "s" process and Europium by the "r" process.

In the halo stars, in the range $-2 \leq [Fe/H] \leq -1$, these elements seems to be slightly less deficient than iron, then their abundance decreases steadily with [Fe/H] up to about [Fe/H]=-3. However the scatter is rather large, several halo stars are known for having a relatively high barium abundance as for example HD115444. This star has also a high Europium abundance. The scatter cannot be explained by measurements errors . In particular, Ryan et al. (1991) and Molaro & Bonifacio (1990) found a very large scatter in the strontium abundance of stars with $[Fe/H] \leq -3.4$. This intrinsic scatter suggests that the early Galaxy was not well mixed.

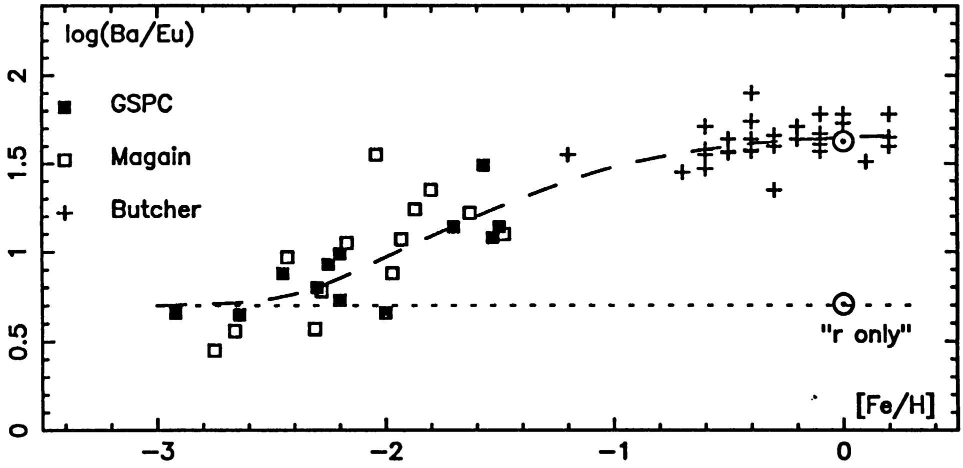

Fig 5. log (Ba/Eu) versus [Fe/H]. The dotted circles represent the solar value of Ba/Eu when either the total abundance of Ba and Eu or only the part formed by *r* process, are taken into account. The abundances have been taken from Butcher(1975), Gilroy et al.(1988) and Magain (1989).

Truran in 1981 remarked that the abundances of the different neutron capture elements in the halo stars strongly suggest a predominantly r-process origin. Gilroy et al. (1988) showed (fig.5) that, in the remote halo, the abundances of Barium and Europium are correlated; the ratio N(Ba)/N(Eu) is the same as the ratio, in the Solar system, of the only "r" process isotopes $N(Ba)_r/N(Eu)_r$ (Lambert 1989). The Ba/Eu behavior could be explained simply by asserting that at the beginning of the Galaxy both Eu AND Ba are pure "r" process elements (i.e. Ba is represented only by its "r" isotopes). Later the "s" process would begin to contribute substantially to the abundance pattern and the ratio [Ba/Eu] rises rapidly to reach the solar value.

However this explanation is not universally accepted: Magain (1989) and Ryan et al. (1991) proposed that at least part of the heavy elements are formed in the halo by the "s" process.

The “s” process is often called “secondary” because it is generally admitted that the first generation of stars (stars without metals), is not able to build the “s” process elements. In this theory, the Sr poor stars would be formed by the material ejected from this first generation of stars.

3. Chemical abundances in globular clusters

With the advent of the CCD detectors, precise measurements of abundances in the globular clusters became available. It is thus possible to compare the abundances in the field halo stars located in the solar vicinity, and in the halo clusters stars. However in the globular clusters only giants and supergiants can be observed. The abundance trends in the globular cluster stars have been recently reviewed by Wheeler et al. (1989) and Gratton (1990). Generally speaking, stars in globular clusters have the same abundance pattern as the field stars of the same metallicity. Possible differences are the abundances of oxygen and of the light metals Na and Al.

oxygen : Generally oxygen is overabundant in the cluster stars as well as in the metal deficient field stars [O/Fe]=0.5 (Pilachowski et al. 1983, Gratton and Ortolani 1989, Brown et al.1991b). However several cluster stars are suspected to be "oxygen poor" ($-0.3 \leq [O/Fe] \leq 0$). Following Brown et al. (1991a), the sum of the CNO nuclides is the same in the oxygen rich and in the oxygen poor stars; the deficiency of oxygen would be thus the signature of a mixing with CNO-cycled material.

the odd Z light metals: Although these elements are rather overdeficient in the halo field stars (fig 3), several cluster stars are known to have very strong aluminum and sodium lines.It has been shown that the strength of these lines is correlated with the strength of the CN band (e.g. Norris and Pilachowski 1985), but that the ratio [Na/Al] varies from star to star (François, 1991).
Gratton (1990) remarks that sodium overabundances (about +0.4 dex) are also observed in the field disk K supergiants (Smith and Lambert 1987) and suggests that these anomalies would be the consequence of severe non-LTE effects on the formation of the lines.
This explanation seems to be not completely satisfactory:

-A systematic overabundance of sodium (about +0.4 dex) is also observed in the field disk F supergiants and it has been shown that this overabundance cannot be explained by departure from LTE (Boyarchuk et al. 1988) .

-Moreover two stars in the same cluster, with about the same atmospheric parameters can have very different abundances of sodium (or aluminum).

The cause of the sodium/aluminum anomalies in the globular cluster stars is up to now not completely clear. The strong Na and/or Al stars in the globular clusters could be perhaps stars which have accreted matter processed in previously evolved AGB stars.

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DISCUSSION

D. Johnson: Recent work by Smith and Lambert may solve the primordial Li abundance quandary. They targeted 5 maximum luminosity AGB stars in the LMC and 2 in the SMC. All seven show incredible Li enhancements. The conclusion is that these stars are producing Li by the Be-transportation mechanism. A simple closed box chemical evolution model shows that the yield from these stars can enrich the disk by a factor of 10 from the halo abundance. Of course with the metallicity differences between the clouds and our Galaxy, detection of such Li producing AGBs in the Milky Way is really needed.

R. de la Reza: Complementing the precedent speaker who mention the discovery of S stars in the Magellanic Clouds as a source of Li, I can say that we discovered other kind of sources of Li in our Galaxy that is Li-rich K giants, one of them having about 10 times larger abundance than the interstellar matter (see poster at this meeting).

M. Pinsonneault: The Spite Li plateau is a beautiful observation which places strong constraints on theory. Models with rotational mixing, however, can nearly uniformly deplete the halo plateau stars by a factor of up to 10. There are also many observations of high Li abundance (~ 3.5 to 3.6) in young stars, which indicates that the current Li abundance is higher than the "cosmic" value of 3.0. So it appears that we need both higher initial Li in halo stars and galactic enrichment

B.Pagel: I should like to report a new twist in the beryllium saga. Steigman & Walker point out that while Be production by cosmic ray spallation in the interstellar medium is proportional to CNO abundance, that of lithium is largely due to α,α collisions and therefore nearly independent of metallicity. Consequently, if Be in halo stars like HD140283 is due to spallation in the interstellar medium, it should be accompanied by a much larger amount of Li which could require significant corrections compared to the amount that is seen and usually ascribed to Standard Big Bang.