Preface

The meeting of IAU Commission 29 on the topic ‘Nucleosynthesis in the Galaxy from the study of low-mass stars’ was held on 27 November 1985 during the XIX General Assembly of the International Astronomical Union, New Delhi. A dozen papers were presented and discussed. The papers presented were of considerable interest, contained many new results and covered several aspects of nucleosynthesis in the Galaxy as inferred from the study of low-mass stars. In fact, it is the first meeting to focus attention on the elemental abundances of low-mass stars.

We publish here ten out of twelve papers presented during the meeting and also an excellent summary and concluding remarks of the meeting presented by Professor B. Gustafsson. We are grateful to the Indian Academy of Sciences for encouragement and support in the publication of these proceedings in the Journal of Astrophysics and Astronomy.

G. Cayrel de Strobel
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Abundances of the Very Light Elements D, He, Li and their Cosmological Implications

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Abstract. The abundances of very light elements D, $^3$He, $^4$He and $^7$Li in low-mass stars and their cosmological implications are discussed.

Key words: abundances, light elements—low-mass stars—cosmology

1. Introduction

The very light elements (D, $^3$He, $^4$He and $^7$Li) are known to be likely produced during the early phases of the universe. The relation between the results of the big bang nucleosynthesis and cosmology has been discussed in other sessions of the Delhi IAU Assembly (J. Audouze, B. E. J. Pagel, G. Steigman). The few remarks I would like to make here regarding this very important problem deal with the relations between the relevant observations in the low-mass stars and the primordial abundances of these very light elements. They concern mainly $^4$He and $^7$Li since D has been destroyed in these stars and is only observed in the interstellar medium and the solar system. Given the lack of information regarding $^3$He, it would be most useful to measure its abundance in low-mass stars for reasons which are presented in the sequel.

2. $^4$He and $^7$Li observations in low-mass stars

Concerning $^4$He a few observations have been made by Carney (1983) in low-mass stars who quotes $Y_p \sim 0.19 \pm 0.05$. This value can be compared with that deduced by Pagel (1986) who from the analysis of blue compact (metal-poor) galaxies derives a primordial $^4$He abundance $Y_p \sim 0.235 \pm 0.005$. Should the primordial abundance of He be as low as the value reported by Carney (1983), the standard big bang model would be in serious difficulty: i.e., prediction of too low a baryonic density from $^4$He compared to that deduced from D and $^7$Li, and number of neutrino families $< 3$ being a value determined by the particle physicists.

In the case of $^7$Li, Spite & Spite (1982) and Spite, Maillard & Spite (1984) have used their observations of the Li abundance in very old and very metal-poor population II stars, and derived the primordial abundance of $^7$Li to be Li/H $\sim 1 - 2 \times 10^{-10}$. Boesgaard & Steigman (1985), in their recent review, estimate the upper limit to the primordial $^7$Li to be Li/H $< 8 \times 10^{-10}$.

3. Implications

From the primordial abundances of D, $^3$He, $^4$He and $^7$Li ($Y \sim 0.235$, $X(D + ^3He) \sim 10^{-4}$ and $X(^7Li) \sim 5 \times 10^{-10}$) and their comparison with the canonical (sim-
plete) big bang nucleosynthesis models one concludes that the baryonic cosmological parameter $\Omega_B \approx 0.10$ and that one should not observe another type of leptons (or neutrinos) than those already known (see e.g. Boesgaard & Steigman (1985) and Steigman (1985) for reviews). Our group (Audouze 1986a, b) is currently arguing that the baryonic cosmological parameters $\Omega_B$ deduced from $^4\text{He}$ and D are consistent only in the case where specific models of chemical evolution of galaxies apply (Delbourgo-Salvador et al. 1985). These models assume a large destruction of D during the galactic life. The observation of the $^3\text{He}$ abundance in the atmosphere of low-mass stars could carry valuable information in that respect: if the abundance of D decreases strongly with time one should determine some relatively large $^3\text{He}$ abundance ratio at the surface of such old stars resulting from the transformation of a large initial D content.

4. Concluding remarks

Low-mass stars cannot by themselves provide all the information which is needed to determine all the primordial abundances of the very light elements D, $^3\text{He}$, $^4\text{He}$ and $^7\text{Li}$. Nevertheless they play a basic role in establishing the primordial abundance of $^7\text{Li}$ and they may provide useful constraint on the chemical models of our Galaxy such as those designed by Delbourgo-Salvador et al. (1985) to reconcile the baryonic densities deduced respectively from $^4\text{He}$ and D. Moreover they might constrain the primordial abundance of He and force the cosmologist to adopt a low value for it which may be inconsistent with the prediction of the standard big bang nucleosynthesis.

Dr Giusa Cayrel deserves my admiration for having been so persistent in making me write this short contribution.

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Pagel, B. E. J. 1986, Highlights in Astronomy, 7, 551.
Li Production in the Big Bang

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Abstract. Li abundance is determined for 23 halo subdwarfs. About half of the stars show [Fe/H] < -1.4 and a space velocity $V > 160$ km s$^{-1}$. Li appears to be present in all our halo stars, with an abundance within about $\pm 0.2$ dex of the value $\log n(\text{Li}) = 2.0$ found by Spite & Spite (1982). Thus our results provide confirmation of the main conclusion of Spite & Spite.

Key words: abundances, Li—cosmology—stars, halo subdwarfs

1. Introduction

Accurate measurements of the abundance of lithium in the surface layers of old and young stars and in the interstellar medium can increase our knowledge of stellar structure, Galactic element production, and big-bang nucleosynthesis. The latter topic has recently been reviewed by Boesgaard & Steigman (1985). Standard models of the hot big bang (e.g., Yang et al. 1984) predict the formation of $\text{D}$, $\text{^3He}$, $\text{^4He}$, and $\text{^7Li}$ in an epoch of primordial nucleosynthesis of a few minutes duration. If the abundances so produced can be measured, they may be used to probe the conditions of the big bang, and to place constraints on particle physics and cosmology.

The primordial abundance of $\text{^7Li}$ is last of these quantities to be probed, in large part because it seemed unlikely that primordial lithium could be detected. Li is the easiest of all elements to destroy. If subjected to temperatures in excess of $2.5 \times 10^6$ K, it is rapidly destroyed by $(p, \alpha)$ reactions. Such temperatures are reached at the base of the convection zones of cool stars, and the Li in these stars is continuously destroyed. The present Li abundance in the Sun is approximately 100 times less than that in the matter from which it formed.

Thus it was a surprising and extremely important discovery by Spite & Spite (1982; hereinafter SS) that Li is present in halo stars of approximately solar temperature, in quantities approximately 10 times larger than in the Sun. Surveying old disc and halo stars, SS, and Spite, Maillard & Spite (1984; hereinafter SMS) found basically that Li is present in stars which have [Fe/H] $< 1.0$, and log $T_e = 3.74 - 3.80$. When detected, the Li abundance was in all cases between 1.9 and 2.2, on the scale $\log n(\text{H}) = 12.0$. The age of the stars and the uniformity of the Li abundance led SS to conclude that they were observing Li produced by the big bang and not modified since then.

The explanation of how such halo stars could presently have more Li than the Sun, despite their greater age, is apparently related to their metallicities. Calculations by Däppen (1984, personal communication) show that as metal abundance is reduced at
fixed log $T_e$, convection zones become thinner and the temperature at their base less. The rate of Li destruction, being extremely temperature-dependent, may be greatly lessened.

What may be a related effect was first noted by Duncan (1981). In studying two phenomena associated with age in solar-type stars, chromospheric activity and Li abundance, he found that although most stars either exhibited high activity and high Li abundances, indicating youth, or low activity and low Li abundance, indicating that they were old, perhaps 15 per cent showed a discrepancy. In all cases the discrepancy was in the sense of low chromospheric activity and high Li abundance. Duncan tentatively concluded that the stars were probably in fact old, and had somehow avoided destroying their Li. The anomalous stars included the most metal-poor stars in Duncan's sample, but no star was more metal-poor than $[\text{Fe/H}] = -0.6$, and not all of the anomalous stars were metal-poor.

Stimulated by the results of SS, the present authors independently set out in 1983 to examine a larger number of subdwarfs chosen to be as homogeneously old as possible. Since both temperature and metal abundance could be expected to affect Li destruction, we set out to survey a large region of the $[\text{Fe/H}], \log T_e$ plane. We have combined our data, and now have spectra of the Li i $\lambda 6707$ doublet at a resolution of typically 0.2 Å for a group of 23 subdwarfs with iron abundances $[\text{Fe/H}] \leq -0.6$ and space velocities $\geq 100$ km s$^{-1}$. About half of these stars in fact show $[\text{Fe/H}] \leq -1.4$ and $V \geq 160$ km s$^{-1}$.

A very preliminary report on some of the most interesting stars is presented here.

2. Observations

A typical spectrum is presented in Fig. 1. Signal-to-noise ratios are generally 100–200. Agreement between our spectra and those of SS are very good. For eleven stars in which we both measured equivalent widths, the mean difference is $2 \pm 5$ mÅ. Every one of our stars which is clearly a halo object shows measurable Li $\lambda 6707$.

3. Temperatures

We have paid particular attention to accurate temperature determination for the stars in our sample. Since Li i $\lambda 6707$ is the resonance line of the neutral species of an atom which is almost completely ionized in these stars, it is very temperature sensitive, and accurate stellar temperatures are needed to derive accurate Li abundances. Peterson & Carney (1979, and additional data in Carney 1983) derived temperatures for most of these stars from matching spectrophotometric scans covering 5,000–8,400 Å to ATLAS6 model-atmosphere surface fluxes, and also from $R-I$ and $V-K$ colours. These three sets of determinations are independent, so random errors should be reduced by averaging them. The discussion which follows concerns differences between stars, in which random errors are the most important ones. Peterson & Carney estimate a random error of 80 K in their temperatures, and a possible 80 K systematic error or zero-point uncertainty. Intercomparison of their three sets of temperatures for each star indicates random errors of approximately 80 K in any one determination from a
Figure 1. Spectrum of HD 134169 showing the upper 40% of the flux.
colour or scan. It appears that Peterson and Carney's estimate of random errors of 80 K in the average of three measurements is conservative.

We conclude that random errors in the present temperature determinations, which are typically based on three independent sets of data, are approximately 60 K. It follows that we can estimate temperature differences between stars with a typical accuracy of about 80 K.

4. Abundances

Curves of growth for Li were computed using the program WIDTH6 (R. L. Kurucz 1983, personal communication) and model atmospheres of Bell et al. (1976). Computations were made for \( T_e = 4500 \text{ K}, 5000 \text{ K}, 5500 \text{ K}, \text{ and } 6000 \text{ K}; [\text{Fe/H}] = 0, -1, \text{ and } -2; \log g = 4.5 \text{ and } 3.75. \) The Li line was treated as a singlet although it is actually a close doublet since previous computations (Duncan 1981) showed this causes negligible error. Atomic parameters were the same as in Duncan (1981). Though there may be small systematic errors in the curves of growth, the dominant source of relative error is the temperature uncertainty. A typical error of 60 K in a star of temperature 5800 K and Li equivalent width 30 mA causes an abundance error of 0.06 dex.

5. Discussion

Li appears to be present in all our halo stars, with an abundance within about ±0.2 dex of the value \( \log n(Li) = 2.0 \) found by SS. Thus our results provide significant confirmation of their main conclusion, that in the halo stars one sees Li which was probably produced in the big bang.

However, we are less certain that it is an unaltered big bang product. Some halo stars of almost exactly the same temperature show differences in Li which may be real. Three examples are listed in Table 1. Although the stars are very similar physically, the Li abundances differ. However, since the temperature uncertainty contributes significantly to the inferred Li abundance, we consider this evidence of differences to be marginal.

The abundance of Li in a wide variety of galactic locations has been found to be approximately \( \log n(Li) = 3.0. \) These include the interstellar medium, young galactic clusters such as the Hyades (Cayrel et al. 1984), the T-Tauri stars, and also lunar samples (Dreibus, Spettel & Wanke 1976), and carbonaceous chondrites (Nichiporuk & Moore 1974). The Pleiades stars which show the least Li depletion (late F stars: Duncan & Jones 1982) also have the same abundance of approximately \( \log n(Li) = 3.0. \) Thus the galactic Li abundance appears constant over at least the last 5 billion yr. The simple monotonic increase suggested by SS (Fig. 5) cannot be correct—it ignores the

<table>
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<th>HD</th>
<th>R - I</th>
<th>V - K</th>
<th>( T_{\text{scan}} )</th>
<th>( T_{R-I} )</th>
<th>( T_{V-K} )</th>
<th>( T_{\text{adopted}} )</th>
<th>[Fe/H]</th>
<th>( W_{\text{Li}} )(mA)</th>
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<td>5810</td>
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<td>1.46</td>
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<td>5840</td>
<td>5780</td>
<td>5800</td>
<td>-1.3</td>
<td>46 ± 3</td>
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Li production in big bang

meteoritic and lunar evidence. If the primordial big bang production of Li is approximately 2.0, a substantial galactic source of Li must have raised the abundance relatively early to \( \log n(\text{Li}) = 3.0 \), but not increased it over the last 5 billion yr.

It also seems possible to us that the big bang production was \( \log n(\text{Li}) = 3.0 \), and that the halo stars have in fact suffered some depletion (10 \( \times \)), but not as much as the Sun (100 \( \times \)). This, of course, depends on the star-to-star differences being real. The star-to-star differences would then represent scatter about the mean depletion curve. (cf. the scatter in Fig. 2 of Cayrel et al. 1984). We suggest that the value \( \log n(\text{Li}) = 2.0 \) be taken as a lower limit to the big bang production.

References


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Recent Work on CNO in Dwarfs and Subdwarfs

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Abstract. The recent results on CNO in dwarfs and subdwarfs are discussed. The value of \([\text{O/Fe}] \approx 0.0\) at solar abundances but gradually increases with decreasing \([\text{Fe/H}]\). The value of \([\text{C/Fe}]\) is constant at \(\approx 0.0^{+1}_{-2}\) as \([\text{Fe/H}]\) declines from \(+0.5\) to \(-2.0\); for \([\text{Fe/H}] < -2.0\), \([\text{C/Fe}]\) increases somewhat reaching a mean value near \(+0.2\) or \(+0.3\) dex. All the investigations agree that N has a strong primary component.

Key words: abundances, CNO—stars, dwarfs and subdwarfs

1. Preliminary remarks and caveats

In attempting to reconstruct the temporal behavior of the CNO group, students of galactic nucleosynthesis would like to have information on the abundances of these elements as closely as possible to the epoch of the formation of the Galaxy. The best the observers can do is to provide data from abundance analyses of the oldest stars. We must be careful, however, to study only those stars in which the atmospheres are uncontaminated by the dredge-up of nuclearly processed material from the interiors. Thus we reject giants and deal only with dwarfs and subdwarfs.

A review (Kraft 1985) of this problem was given only last May at the ESO Workshop on the Origin and Distribution of the CNO Elements where many of the results discussed here are plotted in graphical form. The reader is referred to that article for an extended discussion. Here, I provide only a summary and evaluation of the most recent results.

It must not be supposed that the derivation of CNO abundances is easy: there are many pitfalls and the stumbling blocks are probably greater for N than for C and O. Consequently, results for C and O can be quoted with greater certainty than for N. Briefly, we can catalogue the caveats by element, as follows:

For O: In the hotter subdwarfs, one analyzes the \([\text{O}\,\lambda\,7770]\) triplet near \(\lambda\,7770\), but the lower level of these lines lies at high excitation potential (9 eV) and thus the strengths are particularly sensitive to errors in temperature (recalling that \(kT \sim \frac{1}{2}\) eV). For the cooler subdwarfs, one can use the \([\text{O}\,\lambda\,6300]\) pair near \(\lambda\,6300\), but high spectral resolution is required: in the most metal-poor stars the equivalent widths are of order 10 mÅ. Recently some exciting new results have been derived from the study of the OH molecular features near \(\lambda\,3100\), in the extreme (ground-based) ultraviolet. These will be discussed later in this session (Bessell & Norris 1987).

For C: C is mostly derived from the CH (G-band) feature (\(\lambda\,4300\)) which is strong and spectrosopically accessible in these stars. A small amount of work using atomic C lines has been done, but the atomic lines suffer the same difficulty encountered in the
case of O I lines. Low resolution CH studies can be very reliable if spectrum synthesis is employed, but one has to give up any hope of deriving $^{12}\text{C}/^{13}\text{C}$-ratios.

For $N$: $N$ has sometimes been derived from combining analyses of the CH (G-band) and CN (λ3880) features, but this approach is ill-advised, since a systematic error in C-abundances could introduce a spurious anticorrelation between C and N. Non-LTE effects are especially severe for CN (λ3880), but also may play a role in the analysis of the CH-feature already cited and the NH-feature at λ3360. The latter is far in the (ground-based) ultraviolet and, since the stars are rather red, high signal-to-noise spectra are obtained only with difficulty. Moreover, the dissociation potentials of both NH and CN are imperfectly known. However, low spectral resolution can be employed in the study of both the NH and CN bands if spectrum synthesis is available.

Finally, we note that CO-formation is an important consideration when deriving CH-band-based C-abundances for dwarfs with $T_{\text{eff}} \leq 5500$ K, in contrast to giants in which CO formation plays no role above $T_{\text{eff}} \sim 4500$ K because of reduced atmospheric pressure.

2. Results for oxygen

There is fundamental work by the Texas group on O (summarized by Clegg, Lambert & Tomkin 1981, but see Sneden, Lambert & Whitaker 1979 for the most metal-poor objects), in which the major result is that [O/Fe] $\approx 0.0$ at solar abundance but gradually increases with decreasing [Fe/H] to a more-or-less constant value near $+0.6$ when [Fe/H] $< -1.0$. Bessell & Norris (1987) will report later in this session that [O/Fe] is $\sim +1.3$ in the super metal-poor star CD $-38^\circ$ 245, so there is a slight additional rise with decreasing [Fe/H]. However, [O/Fe] shows some scatter at a given [Fe/H] which is probably real and the present results, based as they are on a sample of only 20 or so stars, need to be supplemented. Systematic errors are difficult to assess, especially since only one group has extensively attacked the oxygen problem, but Gratton & Ortolani (1984) report a study of one metal-poor subdwarf in which they find [O/Fe] = $+0.3$.

3. Results for carbon

The leading recent investigations have been those by Tomkin & Lambert (TL, 1984: high spectral resolution, small sample), Laird (1985: intermediate spectral resolution, sample size $> 100$ stars), and Carbon et al. (1985: low spectral resolution, $\sim 80$ stars). In a plot of [C/Fe] as a function of [Fe/H], these investigations essentially agree in giving [C/Fe] $\sim 0.0^{+0.5}_{-0.1}$ as [Fe/H] declines from $+0.5$ to $-2.0$. The range quoted represents an estimate of the size of possible systematic errors, based on a comparison of investigations, but does not take into account possible errors of analysis that might be common to all (for example, errors introduced by non-LTE effects and from the fact that C and Fe are formed in rather different atmospheric layers).

The Carbon et al. investigation contains a significant sample of subdwarfs with [Fe/H] $< -2.0$ (about 30 stars), whereas almost no very-metal-poor stars are found in the other two samples. This introduces a new element, viz., that for [Fe/H] $< -2.0$, [C/Fe] increases somewhat, to a mean value near $+0.2$ or $+0.3$ dex. Thus it appears
that carbon does not quite perfectly track Fe at very low metallicities, which suggests a partial return to the early Talbot/Arnett (Arnett 1978) nucleosynthetic scenario (cf. Tinney 1979). In the past few days, I received from Chris Sneden a plot of [C/Fe] vs [Fe/H] based on recent high-resolution work by the Texas group which confirms the Lick group finding amongst very metal-poor subdwarfs, so that this carbon 'turn up' now seems quite firmly established.

On the basis of the low-metallicity sample of the Lick group, one finds that the slope of the mean relation between [C/Fe] and \( T_{\text{eff}} \), as \( T_{\text{eff}} \) decreases, depends on the choice of oxygen abundance through CO-formation: the slope is slightly positive if \( [\text{O}/\text{Fe}] = +0.6 \) and negative if \( [\text{O}/\text{Fe}] = 0.0 \). The plot is horizontal if \( [\text{O}/\text{Fe}] = +0.3 \). This result should be compared with the directly derived oxygen abundances and associated caveats cited above, viz., \( [\text{O}/\text{Fe}] = +0.6 \), for stars in this metallicity regime.

Summarizing, we conclude that the run of carbon-to-iron with decreasing [Fe/H] is quite well established, based as it is on a total sample of nearly 200 dwarfs and subdwarfs. The various investigations satisfactorily agree that \( [\text{C}/\text{Fe}] \approx 0.0 \), independent of metallicity from \( [\text{Fe}/\text{H}] = +0.5 \) to \(-2.0 \), but below \(-2.0 \) there is some evidence for a small increase in [C/Fe] of 0.2–0.3 dex.

### 4. Results for nitrogen

Since the NH and CH bands are formed in the same atmospheric layers, we adopt \([\text{N}/\text{C}]\) and \([\text{C}/\text{H}]\) as dependent and independent variables, respectively. This is nearly equivalent to using [Fe/H] as independent variable, but not quite (Section 3). However, the situation in the case of nitrogen is not so firm as for carbon. The best that can be said is that all investigators (Barbuy 1981, 1983; Tomkin & Lambert 1984; Laird 1985; Carbon et al. 1985) agree on the main result, viz., that nitrogen has a strong primary component. However, determination of the precise \textit{ab initio} value, i.e., \([\text{N}/\text{C}]\) when \([\text{C}/\text{H}]\) is below \(-2.0 \), depends strongly on each particular investigation. Both the Barbuy and TL samples are quite small and do not penetrate the domain of lowest metallicities. Altogether in the other two samples, over 150 stars were measured for N-abundance using the NH-bands. They are in reasonable agreement with each other (and are in agreement with TL) for \([\text{C}/\text{H}]\) values above \(-1.5 \); below this value, \( \langle [\text{N}/\text{C}] \rangle \) gradually increases to \( +0.4 \) in the Laird investigation, but contrariwise \( \langle [\text{N}/\text{C}] \rangle \) gradually decreases to \( -0.4 \) in the Carbon et al. investigation. In either case, there is simply too much nitrogen early on to maintain the proposition that N is a 'secondary' element (relative to carbon or iron), following the simple formulation \([\text{N}/\text{C}] \approx [\text{C}/\text{H}]\).

Although a satisfactory explanation for the differences between investigators has not been found, all probably suffer from certain systematic errors. One in particular is actually shared by TL, Laird, and Carbon et al. All show a systematic decrease of \( \langle [\text{N}/\text{C}] \rangle \) with decreasing \( T_{\text{eff}} \); the slope is the same for all and amounts to \( \Delta[\text{N}/\text{C}] \approx 0.4 \) dex over the range \( 6250 \text{ K} \geq T_{\text{eff}} \geq 5000 \text{ K} \). The differing spectral resolution employed by the investigators, ranging as it does from \( R \approx 100,000 \) down to \( R \approx 1000 \), does not seem to have much to do with it: unless one wants to believe that the abundance of N is a function of \( T_{\text{eff}} \) (or equivalently \( M_v \)) along the main sequence, one has to conclude that some error of analysis afflicts all the investigations in more-or-less the same way.
Finally, a few words about 'supernitrogen' stars. In a sample of ~ 25 subdwarfs and dwarfs, Bessell & Norris (1982) uncovered two metal-poor stars with nitrogen abundances enhanced by factors of 10 or more, giving rise to the expectation that such objects might form a quite significant component of the subdwarf population. However the much larger samples of Laird, and Carbon et al. taken together have revealed only two or three additional objects of this kind—four or five altogether—so the actual fraction is in the 1–5 per cent range. Carbon et al. speculated that these stars might have escaped from globular clusters, but evidence cited in the open discussions at New Delhi (Carney) suggests they are members of binary systems, as originally proposed by Bessell and Norris.

References

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Nitrogen Enhancement in Metal-Poor Dwarfs: From Inside or Outside?

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Abstract. The five known metal-poor dwarfs with an enhanced N/Fe ratio have been observed spectroscopically. Two of these dwarfs have no lithium line; the absence of lithium is most probably accounted for by the usual convective destruction. The three other dwarfs have the same lithium abundance as the normal metal-poor dwarfs (Spite, Maillard & Spite 1984). This excludes the deep mixing process as the general source of nitrogen enhancement, since lithium is destroyed in deep (hot) layers. Deep mixing had been previously found unlikely in metal-poor dwarfs (Da Costa & Demarque 1982). The discussion stresses the remarkable uniformity of the lithium abundance in metal-poor dwarfs, and shows that the N-rich contaminating matter has a high N/H ratio. Finally, the Al abundance is not greatly enhanced in these five stars.

Key words: halo dwarfs—nitrogen abundance—lithium abundance—mixing

1. Introduction

Recently, Laird (1985) made a survey of nitrogen abundance anomalies in dwarfs, and among about 40 halo dwarfs he found 4 'nitrogen-rich' dwarfs. We have to clear here immediately two points about the vocabulary. We arbitrarily define halo dwarfs as those that have a metallicity lower than [Fe/H] = −1.0; this limit has already been proposed by Carney (1979), and Spite & Spite (1982). Following Laird, we call the stars 'nitrogen-rich' when the abundance ratio N/Fe is enhanced by more than about a factor of 3 (i.e. ≥0.5 dex). Obviously, since iron is very deficient in the stars discussed here, nitrogen is also deficient: it is only less deficient than the average.

In this way, Laird (1985) confirmed the discovery of two N-rich dwarfs by Bessell & Norris (1982) and added two more dwarfs. Laird proposed three explanations for these anomalies: primordial nitrogen enhancement, binary mass transfer and internal deep mixing.

2. Previous observations

It so happened that, in the course of a program of determination of lithium abundance (Spite & Spite 1982; Spite, Maillard & Spite 1984), we had already observed two of these stars: HD 25329 (Pagel & Powell 1966; Harmer & Pagel 1973) and HD 97916. The lithium line was absent in the spectra of these stars. As a first guess we thought that the

* Based on observations collected at ESO and CFHT.
enhancement of the N/Fe ratio was produced by the mixing of surface with deep layers of the dwarf (near the core) where nitrogen is formed. This would explain the absence of the lithium line, since lithium is destroyed in moderately deep layers of the stars, and more so in very deep layers. However this idea is not very appealing. Such a mixing is expected in globular cluster giants (Sweigart & Mengel 1979), but it seems practically impossible in dwarfs (Da Costa & Demarque 1982). Moreover, the absence of lithium in HD 25329 is normal for such a cool star: the other halo dwarfs of similar temperature have also a low lithium abundance. (Spite, Maillard & Spite 1984; Boesgaard & Steigman 1985).

The case of HD 97916 is more complicated. In an earlier work (Spite & Spite 1982) we found that an empirical limit seemed to exist at about $[\text{Fe/H}] = -1.0$. The dwarfs which had a lower metallicity than this limit (i.e. $[\text{Fe/H}] < -1.0$) suffered no lithium destruction for $T_{\text{eff}} > 5700$ K. The dwarfs which had a larger metallicity than the limit (i.e. $[\text{Fe/H}] > -1.0$) were in the usual situation found in normal or slightly metal-poor stars: some suffered lithium destruction, some not.

The star HD 97916, with a metallicity $[\text{Fe/H}] = -1.1$ does not support the hypothesis of a limit at exactly $[\text{Fe/H}] = -1.0$. Hence Spite, Maillard & Spite (1984) proposed that the limit be pushed to $-1.1$, or preferably, that some kind of progressive effect be considered. Among dwarfs around solar temperature and solar metallicity, about 50 per cent have no detectable lithium (Spite 1982; see also Duncan 1981). Among dwarfs with intermediate metallicity, i.e. $-1.3 < [\text{Fe/H}] < -0.3$, about 30 per cent have no detectable lithium; among very metal-poor dwarfs, i.e. $[\text{Fe/H}] < -1.3$, none is known, up to now, without a 'normal' lithium abundance (see also Duncan & Hobbs 1987; this issue).

These facts can be explained by noting that when the metallicity decreases, the opacity also decreases, which implies that the convection zone becomes shallower, which in turn leads to a smaller chance of lithium destruction. More specifically, the computations of W. Däppen (1982, personal communication; see also Cayrel 1986) show that the internal structure of metal-poor dwarfs is significantly different from the structure of normal dwarfs and should produce an effect similar to the observed one. It is also interesting to note that the limit at $[\text{Fe/H}] = -1.0$ previously proposed by Spite & Spite (1982) was linked with the opacity and internal structure problem. This limit also coincides, by chance, with the value of metallicity that discriminates (although not sharply) between halo and disc stars: such a limit was considered by several authors (see e.g. Carney 1979); this limit is thus linked with the chemical and dynamical evolution of the Galaxy. If we consider now a progressive effect, about the lithium destruction, and no specific limit, the problem of confusion between the two different limits does not arise any more.

Coming back to HD 97916, the lithium destruction in this star is not surprising, since it is only very slightly below the metallicity limit, the difference in metallicity being smaller than the error bar, and lithium destruction has been observed in many other stars at or slightly above the limit. Thus the observation of these two stars leads to inconclusive results, and it appeared interesting to observe the other members of the list of metal-poor N-rich dwarfs.

3. Observations

We observed the two N-rich dwarfs listed by Laird (1985) and the N-rich dwarf also noted by Carbon et al. (1986) who insist that such N-rich stars are very rare (only a few
Nitrogen enhancement in metal-poor dwarfs

per cent of the halo dwarfs). One of these stars was observed at the coudé spectrograph of the CFH 3.6 m telescope and the other two with the CASPEC spectrograph of the ESO 3.6 m telescope. The description of these stars may be found in Table 1.

The analysis of the stars was made by using a grid of model atmospheres by B. Gustafsson (1981, personal communication; Gustafsson et al. 1975). More details about the analysis may be found in another paper (Spite & Spite 1986).

The result is that the three stars (Table 2) have the ‘normal’ lithium abundance of the metal-poor dwarfs (Spite & Spite 1982; Spite, Maillard & Spite 1984). In other words, 4 of the nitrogen enhanced halo dwarfs including HD 25329 have about the same lithium abundance as the nitrogen-normal halo dwarfs of the same temperature. The lithium abundance of the star HD 97916 is easily compatible with the idea that, within error limits, it is not deviating from the lithium abundance of a nitrogen-normal metal-poor star of similar metallicity.

These results point to the conclusion that the lithium abundance has the same behaviour in metal-poor dwarfs either nitrogen-enhanced or not (Fig. 1). This discards any general explanation of nitrogen-enhancement by mixing of the surface with very deep layers of the dwarfs, and some other process has to be responsible for the nitrogen enhancement. Our observations also bring out an interesting information: in order to increase the N/Fe ratio without lowering the Li abundance (the Li/H ratio) the contaminating nitrogen-rich matter had necessarily to have a high N/H ratio.

As previously noted, the nitrogen enrichment observed in some giant stars in globular clusters may be attributed to mixing, but such a mixing should be different from the mixing considered for the dwarfs. Such giants have enhanced sodium and

Table 1. Main characteristics of nitrogen-rich stars.

<table>
<thead>
<tr>
<th></th>
<th>$\log T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>[Fe/H]</th>
<th>Ref.</th>
<th>$[\text{N/Fe}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 25329</td>
<td>3.685</td>
<td>4.0</td>
<td>-1.5</td>
<td>1, 6</td>
<td>+0.45</td>
</tr>
<tr>
<td>HD 74000</td>
<td>3.794</td>
<td>4.5</td>
<td>-1.8</td>
<td>2</td>
<td>+1.7</td>
</tr>
<tr>
<td>HD 97916</td>
<td>3.787</td>
<td>4.0</td>
<td>-1.1</td>
<td>3</td>
<td>+0.8</td>
</tr>
<tr>
<td>HD 160617</td>
<td>3.768</td>
<td>3.5</td>
<td>-1.6</td>
<td>4</td>
<td>+1.7</td>
</tr>
<tr>
<td>HD 166913</td>
<td>3.787</td>
<td>4.3</td>
<td>-1.8</td>
<td>5</td>
<td>+0.7</td>
</tr>
</tbody>
</table>

References:
(2) Peterson (1978a) (5) Laird (1985)
(3) Peterson (1978b) (6) See also Pagel & Powell (1966); Harmer & Pagel (1973)
for nitrogen abundance of HD 25329

Table 2. Abundance of lithium in nitrogen-rich halo dwarfs.

<table>
<thead>
<tr>
<th></th>
<th>$W_{\text{Li}}$</th>
<th>$N_{\text{Li}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 25329</td>
<td>&lt;3</td>
<td>&lt;0.0</td>
</tr>
<tr>
<td>HD 74000</td>
<td>24.5</td>
<td>2.16</td>
</tr>
<tr>
<td>HD 97916</td>
<td>&lt;3</td>
<td>&lt;1.2</td>
</tr>
<tr>
<td>HD 160617</td>
<td>42</td>
<td>2.20</td>
</tr>
<tr>
<td>HD 166913</td>
<td>40</td>
<td>2.17</td>
</tr>
</tbody>
</table>

© Indian Academy of Sciences • Provided by the NASA Astrophysics Data System
aluminium abundances (Cottrell & Da Costa 1981). It is interesting to check if this effect is also present (and stronger) in the N-enriched dwarfs.

In four of the dwarfs, the red Al doublet is not detectable, as it should be if the Al abundance is not greatly enhanced. In HD 97916 the Al doublet is measurable and leads to an abundance [Al/Fe] = +0.12 (François 1986), which is normal for halo dwarfs. These observations show that the aluminum abundance is not greatly enhanced in the N-enriched halo dwarfs.

4. Conclusion

The observations described above show that

1. Lithium is present with 'normal' abundance in three of the nitrogen-enhanced metal-poor dwarfs, absent in the coolest one (as expected) and, not surprisingly, absent in the fifth star. Generally speaking, lithium behaves similarly in N-enhanced and in 'normal' metal-poor dwarfs. This excludes mixing as a general explanation of nitrogen enhancement, since lithium is destroyed in deep layers.

   At this IAU meeting (New Delhi 1985) Bruce Carney and David Latham announced that the metal-poor dwarfs with an enhanced N/Fe ratio are spectroscopic binaries or suspected binaries, so that the final (general) explanation for N enhancement is probably the binary mass exchange.

2. As previously noted (Spite, Maillard & Spite 1984) the lithium abundance of metal-poor dwarfs is noticeably constant and independent of the temperature (for $T_{\text{eff}} > 5500$ K), mass, metallicity (for $[\text{Fe/H}] < -1.0$ or $-1.1$), galactic orbit and eccentricity of the star. These observations show that this abundance is also independent of the N/Fe ratio.

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Nitrogen enhancement in metal-poor dwarfs

3. The contaminating (N-rich) matter has therefore a high N/H ratio, in order to be able to enhance the nitrogen abundance in the star without lowering the lithium abundance.

4. The Al/Fe ratio is not greatly enhanced in these stars.

Acknowledgments

It is not so often that several conclusions may be drawn from the analysis of only 5 stars. This was only possible owing to the work of those who built efficient telescopes, spectrographs and detectors, and maintained them, and also because of those who made extensive surveys and selected the stars which are of special interest. We are especially indebted to R. Cayrel, W. Dąbrowski and P. François for communication of results before publication.

References

Relative Elemental Abundances in Extremely Metal-Deficient Stars

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Abstract. The relative elemental abundances in an extremely metal-deficient star CD−38° 245 with [Fe/H] ~ −4.5 and in similar stars are discussed.

Key words: stars, abundances—stars, metal-deficient

1. Introduction

The composition of field halo stars was recently summarized in an excellent review by Spite & Spite (1985). In this report we will supplement that review by discussing our published results for CD−38° 245, a giant star with [Fe/H] ~ −4.5 (Bessell & Norris 1984), and some unpublished results on nickel and oxygen abundances in extremely metal-deficient ([Fe/H] < −2.0) stars.

Most of the exciting new results in abundance analyses recently have come from the high signal-to-noise red-sensitive detectors such as the reticon and the CCD; however, we have been using a very-blue-sensitive photon-counting system (IPCS) in the ultraviolet (λλ3100–3500) to measure primarily, molecular lines of OH, CH, and NH (Bessell & Norris 1982), and low excitation lines of Ni I, Cr II, Mn II, Ti II, and V II in GK stars of low metallicity. The preliminary results from that work will be discussed here.

There is considerable evidence that oxygen is less deficient than iron in metal deficient objects (cf. Sneden 1985). The abundance of oxygen in cool stars is normally derived from the forbidden O I lines (λ6300, λ6363) in giant stars, and from the O I triplet (λ7772–7775) in hotter dwarf stars. These lines are generally weak in normal stars, either because they are forbidden, or because the excitation potentials of the permitted lines are so high. In metal-deficient stars they become vanishingly small; HD122563 (T_e = 4500 K, [Fe/H] = −2.6) has a [O I] λ6300 line of only 6 mA equivalent width. Bessell, Hughes & Cottrell (1984) computed synthetic spectra of OH lines in GK giants and dwarfs, and showed that these lines can be very strong in extremely metal-deficient models and would serve as a valuable way to derive oxygen abundances when the normal methods are impractical. With the AAT 3.9 m telescope and the IPCS detector we now have OH observations at 3.3 Å mm−1 dispersion or 0.15 Å resolution for eight stars (2 dwarfs, 6 giants) with [Fe/H] < −2.2, including three with [Fe/H] < −3.0. In addition, we determined to derive Ni abundances in CD−38° 245 and other extreme stars to examine the results of Luck & Bond (1983), who found Ni to be overabundant with respect to Fe by up to 0.5 dex at [Fe/H] ~ −2.5. Luck & Bond used Ni lines in the red, but we chose to use the strong Ni lines near λ3400 which would be easily seen in stars as deficient as CD−38° 245. These ultraviolet spectral regions also contain lines of the alpha-rich nuclei Ti, V, Cr, Mn whose relative abundances are of interest in metal-poor stars.
2. Discussion

Ground-based ultraviolet observations are normally considered difficult because of atmospheric absorption; however, although the base extinction is higher than in the blue, the additional ozone absorption component comprises broad shallow bands which are easily removed using the spectrum of a continuous source, such as a broad-line B star. The worse problem is normally the efficiency of the gratings. Most commonly available gratings are blazed for the first or the second order wavelengths in the blue or yellow, and have very low efficiency in the violet; we obtained high efficiency by using a 1200-line grating blazed at $\lambda 3300$ in the third order.

A list of metal lines was selected for the region $\lambda 3100$–$\lambda 3200$ from the Utrecht Solar Atlas (Moore, Minnaert & Houtgast 1966). Oscillator strengths were taken from references given by Miller, Fuhr & Martin (1980), or if unavailable, from Kurucz & Peytremann (1975). This short list was adequate for the hotter ($T_e > 4700$ K) and most metal-deficient stars, but for the stronger-line stars it was apparent that a more complete list of metal lines was necessary. Kurucz (1986, personal communication) recently has kindly sent us a provisional list based on his computations, and we will use this data for the final analyses. The OH line list was described in Bessell, Hughes & Cottrell (1984), and was taken from Goldman & Gillis (1981).

In Fig. 1 is shown a part of the observed spectrum for the extreme subdwarf HD140283, [Fe/H] = $-2.65$, $T_e = 5650$ K, log $g = 3.50$, in the vicinity of the CH $C - X$

![Figure 1](image_url)

**Figure 1.** Observed spectrum of HD 140283 (heavy line) compared with a series of synthetic spectra with [O/Fe] = $-2.0$, 0.0, +0.5 and +1.0 dex. The best fitting synthetic spectrum has [O/Fe] $\sim$ +0.9 dex.
Abundances in extremely metal-deficient stars

band; many strong OH lines from the (0, 0) and (0, 1) bands dominate the spectrum. Superimposed are the synthetic spectra corresponding to four values of [O/Fe], −2.0 dex (zero oxygen), +0.5, +1.0 dex. Clearly an overabundance of [O/Fe] ~ +0.9 is indicated. Six other halo stars with similar Fe abundance gave similar O overabundance and in a very exciting observation we detected OH in CD −38° 245 ($T_e = 4500$ K, log $g = 2.0$, [Fe/H] = −4.5) yielding [O/Fe] = +1.3.

Fine-analyses using WIDTH6 (Kurucz 1975, personal communication) were made for individual unblended lines of Ni II, Ti II, Cr II, Mn II and V II measured in the $\lambda$3360–$\lambda$3500 and $\lambda$3100–$\lambda$3200 regions. No evidence was found for Ni overabundance in any of the stars observed, including two found most overabundant by Luck & Bond (1983). Barbuy, Spite & Spite (1985, and references therein), and Leep & Wallerstein (1981) also find no evidence for Ni overabundance in three very-metal-poor stars. The alpha-rich elements showed the expected odd-even abundance effect, and the overabundance of Ca and Ti, relative to Fe, seen in previous analyses of metal-poor stars is seen to be the case for the alpha-rich elements in general.

In Fig. 2 are plotted schematically the relative abundances of HD2796 an archetypal [Fe/H] = −2.4 giant, and CD −38° 245. The data are taken from Bessell & Norris (1984), supplemented with the data discussed here. It is clear that the character of the relative abundances in the two stars is similar and that we are probably seeing the underlying trends of element synthesis in the early stages of galactic chemical enrichment. We are continuing the search for more extreme metal-poor stars [Fe/H] < −3.0, to find how uniform these chemical enrichment processes were in the field. The increasing use of echelle spectrographs and the possibility of using high signal-to-noise blue-sensitive CCDs will produce remarkable improvements in our knowledge of abundances of metal-poor systems in the next few years.

![Figure 2. Relative abundances of HD 2796 and CD −38° 245.](image-url)
References

Chemical Evolution of the Galaxy: Abundances of the Light Elements (Sodium to Calcium)

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Abstract. The abundances of the light (Na to Ca) elements in disc and halo stars are reviewed. New analyses are emphasized. Elements considered are the $\alpha$-nuclei (Mg, Si, and Ca), and the odd-even nuclei (Na and Al, also $^{25}\text{Mg}$ and $^{26}\text{Mg}$).

The $\alpha$-nuclei are overabundant (relative to Fe) in the old disc and halo stars. Halo stars ($[\text{Fe/H}] < -1.2$) have $[\alpha/\text{Fe}] \sim 0.3$ with extreme halo ($[\text{Fe/H}] \lesssim -2.0$) stars showing possibly higher overabundances. The scatter in $[\alpha/\text{Fe}]$ at a given $[\text{Fe/H}]$ is small. To within the observational errors, the abundance patterns for Mg, Si, and Ca are identical.

For disc stars, the Na and Al abundances relative to Mg are almost independent of the $[\text{Fe/H}]$. Halo stars ($[\text{Fe/H}] < -1$) show $[\text{Na/Mg}] < 0$ and $[\text{Al/Mg}] < 0$, but the form of the mean relation and the scatter about the relation between $[\text{odd-even/Mg}]$ and $[\text{Fe/H}]$ remains uncertain.

Key words: Galaxy, chemical evolution — abundances, light elements

1. Introduction

This brief review examines the status of determinations of the abundances of the light elements — sodium to calcium — in stars of differing metallicities (i.e., iron abundance). The review may be timely in as much as new results of unprecedented precision are becoming available as high quality, high resolution spectra are obtained and analysed in increasing numbers. Application of solid-state detectors such as the Reticon and charge-coupled device are revolutionizing quantitative stellar spectroscopy. For the galactic disc population which is well represented by bright stars, the revolution is providing abundances of high accuracy; an aim of this review is to illustrate this accuracy. For the halo population, the initial impact of the revolution will be to enlarge the sample of analysed stars with reliably determined abundances.

Throughout the review, ‘the $X$ abundance’ is taken to be the ratio of $X$ to hydrogen by number of atoms. I denote this ratio by $\varepsilon(X)$ and usually give log $\varepsilon(X)$ on the standard scale such that log $\varepsilon(\text{H}) = 12.0$. For convenience, stellar abundances are often referenced to the solar values. Then, the standard notation

$$[X] = \log \varepsilon(X)_{\text{star}} - \log \varepsilon(X)_{\text{sun}}$$

is adopted. In much of the discussion, I examine how the abundances of the light elements vary with respect to iron, i.e., I consider the change of $[\text{light}/\text{Fe}]$ with $[\text{Fe/H}]$. © Indian Academy of Sciences • Provided by the NASA Astrophysics Data System
Iron is a spectroscopically convenient choice as a representative of the iron-peak. Reference of the light elements to the iron-peak is a significant step because the two groups may well have different nucleosynthetic origins. I define ‘light elements’ to be bounded by Na and Ca.

Too little information is available on the evolution of the He abundance over its big-bang level. Lithium, beryllium and boron abundances reflect a different set of production and destruction processes to those betrayed by the light elements. Carbon, nitrogen, and oxygen abundances in metal-poor stars are discussed by Kraft (1987) in this volume. Fluorine and Ne are omitted for lack of information on their abundances in stars. With a study of the light elements in stars of differing metallicity (i.e., determinations of [light/Fe]), the iron-peak is brought within the scope of the review; I do not, however, discuss the metallicity–age relation.

The main thrust here is to pose and answer a few simple questions about the abundances of the light elements:

What is the mean relation between [light/Fe] and [Fe/H] in the disc and the halo?

Is the scatter in [light/Fe] at a given [Fe/H] significantly greater than the measurement errors?

Do the even-even (or α) nuclei (e.g., 24Mg, 28Si) and odd-even nuclei (e.g., 23Na, 27Al, 25Mg) show different trends with metallicity?

Few interpretive remarks are provided to relate the abundances to the theory of stellar nucleosynthesis. The emphasis is on new results for the light element abundances. I omit P, S (Clegg, Lambert & Tomkin 1981), Cl, Ar, and K (Gratton & Sneden 1986) for which little or no information is available. In a concluding section, I sketch the variation of [X/Fe] with [Fe/H] for the light elements as well as additional groups of elements (CNO, the s- and r-process heavy elements) in both disc and halo stars.

2. A survey of the abundances

2.1 Recent Investigations

With the advent of new spectrometers of high sensitivity, several studies of the abundances in metal-poor stars have been completed recently. Although constraints of time and space discourage me from attempting a complete cataloguing and critical discussion of the many earlier publications on the abundances in metal-poor stars, I must emphasize that the gross systematics of the abundance variations were uncovered long ago. Certain key references are provided. I apologize to any author whose papers have been (apparently) overlooked.

Five recent papers are the basis for my discussion:

1. Tomkin, Lambert & Balachandran (1985, hereinafter TLB): High-resolution red and near-infrared Reticon spectra from the McDonald Observatory were used with scaled solar (Holweger & Müller 1974) models and solar gf-values to derive Na, Mg, Al, Si, Ca, Sc, and Fe abundances for 20 F, G, or K dwarfs of the galactic disc ([Fe/H] ≥ −0.9). Effective temperatures were taken from colours and the Hβ index and published calibrations (see Clegg, Lambert & Tomkin 1981, hereinafter CLT). Surface gravities were computed from the absolute magnitudes, the effective temperatures, and estimates of the stellar mass (see CLT).
2. Luck & Bond (1985, hereinafter LB): Image-tube echelle spectrograms of 36 metal-poor field red giants, solar gf-values, MARCS model atmospheres (Gustafsson et al. 1975; Bell et al. 1976), and a LTE line analysis program provide abundances for a range of elements from oxygen to europium. The appropriate $T_{\text{eff}}$ and log $g$ for the model were determined from the Fe i and Fe ii lines by the usual means. Of the light elements, Mg and Ca are best represented, with useful data also provided for Si. Unfortunately, the odd-even pair—Na and Al—are represented by just one or two lines and in only a few of the 36 stars. The value of the sample is that all but two of the stars belong to the halo; i.e., $[\text{Fe/H}] < -1.0$ with a minimum and a mean abundance of $-3.0$ and $-1.9$, respectively.

3. Nissen, Edvardsson & Gustafsson (1985, hereinafter NEG): High-resolution Reticon spectra from ESO’s coudé echelle spectrometer (CES) provide high S/N spectra of 29 disc dwarfs of F type in selected intervals from which abundances of a selection of light through heavy elements are derived using MARCS models and solar gf-values. The basic parameters—$T_{\text{eff}}$ and log $g$—are computed from Strömgren photometric indices.

This analysis appears to be the most precise of the quintet highlighted here; for example, the rms scatter of the $[\text{Fe/H}]$ values from about 20 Fe i lines is only 0.05 dex for a typical star—all values fall within $\pm 0.10$ dex of the mean. The light elements available are Na, Mg, Al, Si, and Ca. Titanium which behaves much like an $\alpha$-element was also included along with Ni, and the heavy elements Y and Ba.

4. François (1986, hereinafter F): High-resolution Reticon spectra from the CES at ESO and the coudé spectrometer of the CFHT provide abundances of Na, Mg, Al, Si, and Fe in up to 36 field dwarf stars including a few halo stars. Defining parameters—$T_{\text{eff}}$ and log $g$—were taken from published analyses as provided by the ‘Catalogue of [Fe/H] Determinations’ (Cayrel de Strobel et al. 1985). MARCS models with solar gf-values were adopted for the abundance analysis.

5. Gratton & Sneden (1986, hereinafter GS): This ambitious survey of the light elements examined 62 stars of types F, G, K and luminosity classes V to III with known iron abundances, and belonging to the metal-rich disc to the extreme halo. Approximately half of the sample belong to the halo (i.e., $[\text{Fe/H}] < -1$) and one quarter to the extreme halo (i.e., $[\text{Fe/H}] < -2$). High resolution spectra were acquired at the McDonald and ESO observatories using various detectors (Reticon, Digicon, CCD). The method of abundance analysis incorporates MARCS models and solar gf-values. A star’s $T_{\text{eff}}$ was derived from colour indices. The surface gravities for dwarfs were calculated from the $M'_V$'s, bolometric corrections, and an assumption about the stellar mass (0.7 to $1.0 M_\odot$ according to absolute luminosity). For the giants, the surface gravities appear to be based primarily on the stellar spectroscopists’ customary insistence that neutral and ionized lines of the same element (often, Fe) yield the same abundance. Light elements generally examined were Na, Mg, Al, Si, Ca, and K (also Ti). The iron peak was represented by Fe in all stars, Ni in almost all stars, and Sc and V in many stars.

Space (and time) limitations prevent me from providing a critical assessment of these abundance analyses. I shall let the plots of the abundance variations ($[X/\text{Fe}]$ versus $[\text{Fe/H}]$) portray the remarkably high degree of agreement and betray the few remaining irritating inconsistencies between these (and other) investigations of the evolution of light elements.
2.2 The $\alpha$-Elements

The $\alpha$-elements provided to varying levels of completeness by the five sources are Mg, Si, and Ca. In Fig. 1, I show [Si/Fe] versus [Fe/H] for four of the samples; the fifth (LB) is the only sample to be based on photographic spectra. Each of the $\alpha$-elements shows a similar trend with declining Fe abundance. In an attempt to reduce the scatter, I computed the mean abundance (see Fig. 2). This mean is based on at least two of the three $\alpha$-elements. Inspection of these two figures shows that the scatter at a fixed [Fe/H] is reduced noticeably in Fig. 2 relative to Fig. 1. I suggest that this reduction results from a partial cancellation of measurement errors when the mean [$\alpha$/Fe] is computed. In Figs 3 and 4, I compare the Mg and Ca abundances given by the two sources (LB and GS), that provide a thorough sample of halo stars, and by Peterson (1981, hereinafter P), whose careful analyses are based on photographic high-dispersion spectra of old disc and halo dwarfs. Finally, Fig. 5 compares the mean [$\alpha$/Fe] abundances versus [Fe/H] for the LB and GS samples; the contributors to the means are Mg and Ca, for LB's sample, and Mg, Si, and Ca, for GS's samples.

How does the abundance of $\alpha$-elements vary relative to the iron abundance in disc and halo stars? Examination of Figs 2 and 5 suggests the following variations:

In stars of approximately solar metallicity, [$\alpha$/Fe] is apparently constant. The mean value may be slightly positive; i.e., the Sun is apparently slightly deficient in the $\alpha$-elements. The scatter in [$\alpha$/Fe] is small.

---

Figure 1. [Si/Fe] as a function of [Fe/H] for the samples analysed by GS, TLB, F, and NEG. Giants (log $g < 3.0$) in GS's sample are denoted by crosses, and dwarfs and subgiants (log $g \geq 3.0$) by open squares. The points corresponding to the two K0 dwarfs in TLB's collection of dwarfs are placed in parentheses. The identical lines drawn through the data are approximate fits, not least-squares solutions.
[\alpha/Fe] as a function of [Fe/H] for the samples analysed by GS, TLB, F, and NEG. See caption to Fig. 1 for comments on the symbols. The elements contributing to [\alpha/Fe] are Mg, Si, and Ca for the GS, TLB, and NEG samples and Mg and Si for F's samples. For those stars where the abundance of one of the contributors to the mean [\alpha/Fe] was unavailable, the symbol is underlined. Several stars for which GS provide just one of the three contributing abundances are not plotted. The lines drawn through the data are approximate fits and are identical except for slight offsets in [\alpha/Fe].

In metal-poor disc stars, [\alpha/Fe] increases approximately linearly with decreasing [Fe/H]. This increase begins at [Fe/H] = -0.2 \pm 0.1 and terminates at [Fe/H] = -1.2 \pm 0.1. The scatter in [\alpha/Fe] at a given [Fe/H] is small.

In halo stars, [\alpha/Fe] is approximately constant with that [\alpha/Fe] = +0.3 \pm 0.05 relative to its value in stars of solar metallicity. The scatter (Fig. 5) in [\alpha/Fe] at a given [Fe/H] may be larger than in the disc stars.

On the figures, we represent this variation of [\alpha/Fe] by lines constructed according to the prescription

\[
[\alpha/Fe] = A_\alpha \quad \text{for} \ [Fe/H] \geq -0.15, \\
[\alpha/Fe] = A_\alpha - 0.286 ([Fe/H] + 0.15) \quad \text{for} \ -1.2 \leq [Fe/H] \leq -0.15, \\
[\alpha/Fe] = A_\alpha + 0.30 \quad \text{for} \ [Fe/H] < -1.2.
\]

The constant $A_\alpha$ = 0.05 appears to fit most of the data; i.e., the Sun appears to be slightly $\alpha$-poor relative to the majority of stars of the same metallicity. However, systematic errors are likely to be of the same order of magnitude; e.g., a revision of the temperature scale by about 100 K suffices to reduce $A_\alpha$ to zero for Mg and Si. Furthermore, the many similarities between the five (and other) selected recent analyses ensure that all may be afflicted by similar systematic errors. It would be interesting to undertake a detailed analysis of the Sun and stars in order to determine both $A_\alpha$ and the intrinsic
Figure 3. $[\text{Mg/Fe}]$ as a function of $[\text{Fe/H}]$ for the samples analysed by LB, GS and Peterson (1981; hereinafter, P). Giants ($\log g < 3.0$) in GS's sample are denoted by open squares, and dwarfs and subgiants ($\log g \geq 3.0$) by filled squares. The identical lines drawn through the data are approximate fits based on data in Figs 2 and 5.

Figure 4. $[\text{Ca/Fe}]$ as a function of $[\text{Fe/H}]$ for the samples analysed by LB, GS, and P. See caption to Fig. 3 for comments on the symbols and the lines.
scatter in [$\alpha$/Fe] at [Fe/H] $\sim$ 0.0. On the present evidence (Fig. 2), the scatter in [$\alpha$/Fe] is less than about $\pm$ 0.03 dex, a value certainly dominated by the measurement errors, and $A_{\alpha}$ apparently differs from the mean [$\alpha$/Fe] by an amount exceeding 0.03 dex. The remarkably small intrinsic scatter must constrain theories of stellar nucleosynthesis.

The increase of the $\alpha$/Fe abundance ratio in metal-poor disc stars is not a novel result of the recent analyses. An increase was noted first (?) by Wallerstein (1962) from an analysis of 31 G dwarfs. Many studies on a variety of stellar samples have now provided evidence for the mean trend summarized in our figures and by the formulae given above. The most recent analysis of Mg (Laird 1986) appeared as the final draft of this paper was being prepared. Laird derives the Mg abundance from synthetic spectra fitted to 43 Å mm$^{-1}$ image-tube spectra providing the Mg I b lines in 111 dwarfs. For approximately 90 disc stars ([Fe/H] $> -1$), Laird's least-squares fit gives

$$\frac{[\text{Mg/Fe}]}{[\text{Fe/H}]} = -(0.28 \pm 0.02)[\text{Fe/H}] - 0.06(\pm 0.02).$$

The coefficient (-0.28) is identical to mine. The offset (my $A_{\alpha}$) is here negative rather than positive. However, such a difference may well reflect the systematic errors, as Laird's analysis in contrast to others is based exclusively on lines that are very strong in field disc dwarfs. Inspection of Laird's results shows that they permit a transition to [$\alpha$/Fe] = $A_{\alpha}$ at [Fe/H] $\sim$ -0.2. For the halo ([Fe/H] $<-1$), Laird obtains a mean [$\alpha$/Fe] = +0.24 $\pm$ 0.13 (s.d.) from 22 stars and, hence, to a 0.30 increase above the value at [Fe/H] = 0.0, an increase precisely equivalent to that given by our prescription.

Perhaps, the leading outstanding questions about the $\alpha$/Fe ratio concern its behaviour in the halo. The simplest assumption consistent with most of the published abundances is that [$\alpha$/Fe] is constant below [Fe/H] $\sim$ -1 with an observed scatter which is small (say, $\pm$ 0.15 dex) and is dominated by the measurement errors. Figs 1 through 5 confirm this assumption except for two deviations:
1. The scatter in [$\alpha$/Fe] according to GS is rather larger than assumed. The scatter is
$\pm 0.4$ dex in [Mg/Fe] (Fig. 3) and $\pm 0.3$ dex in [$\alpha$/Fe] (Fig. 2).

2. LB's result show [$\alpha$/Fe] to increase slightly in the extreme halo stars ([Fe/H] < -2) (Fig. 5).

An assumption that the intrinsic scatter in [$\alpha$/Fe] for halo stars is small is not
necessarily compatible with the theories of Galactic chemical evolution. If the $\alpha$
-elements and the iron-group are synthesized in different stars, and gas clouds in the
early Galaxy were poorly mixed, one may expect, as earlier and earlier generations of
stars are examined, [$\alpha$/Fe] to show an increasing scatter with decreasing [Fe/H]. Also,
halo stars now in the solar neighbourhood and having the same [Fe/H] may have come
from more diverse birthplaces than the disc stars. Is the scatter portrayed by GS's
results for halo stars a reflection of an intrinsic scatter? First, we note that some earlier
studies based on spectra of ostensibly inferior quality do not show such a large scatter;
note Fig. 5 where the scatter in [$\alpha$/Fe] for LB's sample is slightly smaller than for GS's
sample. Second, we draw attention to the sudden onset of the scatter that is seen clearly
in Figs 1 and 3 where the small scatter in [Si/Fe] and [Mg/Fe] for disc stars is
insufficient to mask the trend with [Fe/H], but the scatter in the halo suddenly and
dramatically increases between [Fe/H] $\sim -1.5$. A dominant contributor to the scatter is
the set of abundances based on CASPEC CCD-spectra. In fact, GS place low weight on
the abundance derived from ESO's CASPEC and even omit the 'CASPEC' abundances
from several plots. The lines of Mg i, Si i, and Ca i are extremely weak and the available
spectra are too noisy to permit reliable measurements. The problems are not inherent
to the CCD-equipped CASPEC because several investigators have lauded its ability to
provide high quality spectra (see Spite, François & Spite 1985). We suggest that the
totality of present evidence does not demand that the scatter in [$\alpha$/Fe] at a given
[Fe/H] be markedly greater in halo than in disc stars.

If GS's 'CASPEC' abundances are disregarded, LB's study is the only one to provide
data on more than just one or two extreme halo stars. Fig. 5 offers a hint that [$\alpha$/Fe] in
the halo increases either steadily with declining [Fe/H] below [Fe/H] $\sim -1$ or more
rapidly below [Fe/H] $\sim -2$ after remaining level between [Fe/H] = -1 and -2. We
offer this hint as an incentive to observers. By way of supporting evidence, we note that
the [Fe/H] $\sim -2$ is also the point below which LB report a steady increase in [Ni/Fe]
(see also Luck & Bond 1983), and a slight decline in [Ti/Fe]. Other changes occur at or
near this metallicity. There is a deficiency of s-process elements beginning near
[Fe/H] = -1.5 (Spite & Spite 1978; Spite 1983, and LB). Carbon appears to increase in
abundance relative to iron beginning at [Fe/H] $\sim -1.8$ (Tomkin, Sneden & Lambert
1986). There is contrary evidence on some of these changes. In particular, the [Ni/Fe]
trends have been challenged. Magain (1985) reports [Ni/Fe] = +0.05 for HD 19445
with [Fe/H] = -2.33, and +0.08 for HD 140283 with [Fe/H] = -3.00. LB's expected
results for these stars are [Ni/Fe] = +0.2 and +0.6 respectively.

2.3 Na and Al

Nucleosynthetic yields of odd-even nuclei such as Na and Al are expected (from carbon
burning) to be lower than the yields of the even-even or $\alpha$-nuclei such as Mg and Si.
Both Arnett's (1971) theoretical study of explosive C burning and more recent
calculations by Woosley & Weaver (1982) of hydrostatic C burning in massive stars predict lower yields for Na and Al. Even with the new abundance analyses, the observational picture on the ratio of the odd-even/even-even nuclei such as $^{23}\text{Na}/^{24}\text{Mg}$ and $^{27}\text{Al}/^{28}\text{Si}$ is cloudy. Both $^{22}\text{Na}$ and $^{27}\text{Al}$ are the sole stable nuclides of these elements. Although $^{24}\text{Mg}$ and $^{28}\text{Si}$ are the most abundant nuclides, the atomic lines necessarily provide the total elemental abundances—i.e., $\text{Mg} = ^{24}\text{Mg} + ^{25}\text{Mg} + ^{26}\text{Mg}$ and $\text{Si} = ^{28}\text{Si} + ^{29}\text{Si} + ^{30}\text{Si}$. However, the heavier isotopes provide only about 20 per cent (Mg) to 8 per cent (Si) of the elemental abundance in stars of near solar metallicity, and this fraction is known to decline with decreasing metallicity (see below). Therefore, we may identify Mg, Si, and Ca as effectively pure $\alpha$-elements.

Prior to the completion of some of the recent analyses, one could claim that the longstanding confusion about the Na and Al abundances in halo stars was close to resolution. Fig. 6 from TLB provides the basis for this claim. With the sole exception of two stars analysed by Spite & Spite (1980), $[\text{Al}/\text{Mg}]$ fits the following prescription:

$$[\text{Al}/\text{Mg}] = A_{\text{Al}} \quad \text{for} \quad [\text{Fe}/\text{H}] \geq -1.0,$$

$$[\text{Al}/\text{Mg}] = [\text{Fe}/\text{H}] + 1.0 + A_{\text{Al}} \quad \text{for} \quad -2.5 \leq [\text{Fe}/\text{H}] \leq -1.0,$$

$$[\text{Al}/\text{Mg}] = -1.0 + A_{\text{Al}} \quad \text{for} \quad [\text{Fe}/\text{H}] \leq -2.0.$$  

![Graph](image-url)

**Figure 6.** $[\text{Na}/\text{Mg}]$ and $[\text{Al}/\text{Mg}]$ as a function of $[\text{Fe}/\text{H}]$ for the F and G dwarfs analysed by TLB (filled circles) and others (open circles: Peterson 1981; open squares: Spite & Spite 1980; filled triangles: Arigony & Magain 1983; plus sign: Tomkin & Lambert 1980; cross: Carney & Peterson 1981). Lines join the points for HD 19445 and HD 140283, which have been the subjects of multiple investigations; HD 140283 is the more metal-deficient of the two stars.
where $A_{\text{Al}} \approx 0.0$. Note that $[\text{Fe}/\text{H}] \sim -2$ again appears as the point at which a change of the chemical composition of the extreme halo occurs.

In providing this prescription and the accompanying assumption that the scatter in $[\text{Al}/\text{Mg}]$ at a given $[\text{Fe}/\text{H}]$ is small, we dismiss the two points near $[\text{Al}/\text{Mg}] \sim 0.0$ contributed by Spite & Spite (1980). The third such star analysed by them was HD 140283 which was reanalysed by Arpigny & Magain (1983; see also Magain 1985) who discovered that one of the two Al resonance lines used by Spite & Spite and by others is blended with a CH line. For this and other reasons, Arpigny & Magain (see Fig. 6) obtained a much lower $[\text{Al}/\text{Mg}]$ value for HD 140283. TLB supposed that the halo stars showing $[\text{Al}/\text{Mg}] \sim 0$ would, on reanalysis, conform to the simple prescription, and show $[\text{Al}/\text{Mg}] \sim -1$. With the limited data on Na available to TLB, one can claim no more than that to $[\text{Fe}/\text{H}] \sim -1.5$, $[\text{Na}/\text{Mg}] \sim [\text{Al}/\text{Mg}]$.

After this introduction, I return to the new studies. In Fig. 7, I show $[\text{Na}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ from the samples considered by GS, TLB, F, and NEG. For disc stars, the four studies provide concordant results. Only GS and F considered halo stars, and the latter’s sample is perhaps too small for a meaningful check on the large scatter formed by GS for halo stars. Since Na, Al and the $\alpha$-elements, but not Fe, are formed in the same sites, a ratio such as $[\text{Na}/\text{Mg}]$ is more meaningful than $[\text{Na}/\text{Fe}]$; later, we comment on $[\text{Mg}/\text{H}]$ as an alternative to $[\text{Fe}/\text{H}]$. Fig. 8 shows $[\text{Na}/\alpha]$ versus $[\text{Fe}/\text{H}]$ for the samples considered by GS, F, and NEG. Fig. 9 gives the equivalent plot for $[\text{Al}/\alpha]$. The lines fitted by eye to the data follow the prescription given above with $A_{\text{Al}}$ (or $A_{\text{Na}}$) as the

![Figure 7](image_url)

**Figure 7.** $[\text{Na}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ for the samples analysed by GS, TLB, F, and NEG. See caption to Fig. 1 for comments on the symbols.
Figure 8. \([\text{Na}/\alpha]\) as a function of \([\text{Fe}/\alpha]\) for the samples analysed by GS, F, and NEG. See captions to Figs 1 and 2 for comments on the symbols. The line fitted by eye to the points (the disc stars are emphasized here) is described in the text. It is an approximate fit to the points plotted in Fig. 6.

Figure 9. \([\text{Al}/\alpha]\) as a function of \([\text{Fe}/\alpha]\) for the samples analysed by GS, F, and NEG. See caption to Fig. 8 for explanation of the symbols and the line.
sole free parameter. The fits are made emphasizing the disc stars for which all studies are in broad agreement.

Comparison of Figs 6, 8, and 9 suggest that the new studies have not clarified the evolution of the Na and Al abundances through the halo to the disc. Fair agreement now exists on these abundances in the disc ([Fe/H] < -1): [Na/α] and [Al/α] are independent of [Fe/H]. One cannot exclude a slight increase of the ratios with [Fe/H], say by 0.1 dex between [Fe/H] of -1 and 0. The scatter in [Na/α] reported by GS and F is presumably attributable to measurement errors. Certainly, this scatter exceeds that exhibited by TLB's and NEG's samples. François's few halo stars deviate slightly from the prescription based on Fig. 6. If his stars are representative and the scatter in composition among halo stars is small, minor modifications to the prescription suffice to achieve a compromise; say, adopt [Fe/H] ~ -2.5 as the point below which [Al/α] and [Na/Mg] assume an approximately constant value. A far larger deviation from the prescription is provided by GS's sample. It would appear that the prescription is a fair fit to the lower envelopes of GS's points in both Figs 8 and 9. If the stars with [Fe/H] < -2.0 were rejected from the sample, GS's results would fit the prescription with one of the possible minor modifications suggested by F's results. GS remark that their Na abundances for [Fe/H] < -2.0 are based on the Na I D lines which, being on the flat portion of the curve of growth, are less than ideal as abundance indicators. GS do not identify a similar specific reason for supposing that the Al abundances of the extreme halo stars be assigned a low weight; the one unblended Al I resonance line may be partially blended at the lower resolution of the CASPEC spectra. I suspect that the dominant contribution to the scatter in the results both [Na/α] and [Al/α] for extreme halo stars is observational rather than intrinsic. I note that GS omit those points based on the CASPEC spectra in compiling several plots showing abundance trends.

LB's analyses of Na and Al provide little additional information because the pair are 'poorly represented' on the echelle spectra. For Na, LB have 10 stars with 
\[
-1.5 < [\text{Fe/H}] < -1.0
\]
which provide mean values of [Na/α] = -0.24 and [Fe/H] = -1.33 (or [Na/α] = -0.34 if one very discrepant star is dropped). These values fall close to the prescription. Two stars with [Fe/H] < -2.0 have [Na/α] > 0 and apparently fall well above the prescription. For Al, the means in the same ranges are
\[
[\text{Al/α}] = +0.13 \quad (4 \text{ stars with a mean } [\text{Fe/H}] = -1.31) \quad \text{and} \quad -0.37 \quad (4 \text{ stars with a mean } [\text{Fe/H}] = -2.35).
\]
The [Al/α] value for the extreme halo drops to -0.67 when one star with an apparently discrepant value (+0.54) is discarded; the other three values are 
\[
-0.62, -0.56, \text{ and } -0.83.
\]
These [Al/α] values are about 0.3 dex above the value derived using the prescription.

Any odd-even isotope of a light element should serve to test the predictions of stellar nucleosynthesis. Recently, attempts have been made to extract the $^{24}\text{Mg}/^{25}\text{Mg}/^{26}\text{Mg}$ ratios from the Mg H $A-X$ transition whose lines are present in cool stars. The isotopic ratios were earlier obtained for sunspots (Sotirovski 1971), and K and M giants (Boesgaard 1968; Bell & Branch 1970; Tomkin & Lambert 1976, 1979). An initial attempt to examine a metal-poor dwarf was made by Tomkin & Lambert (1980) who reported upper limits on the $^{25}\text{Mg}$ and $^{26}\text{Mg}$ abundances which were less than the solar/terrestrial values: $^{1}\text{Mg}/^{24}\text{Mg} < 7$ per cent, but $^{1}\text{Mg}/^{24}\text{Mg} = 13$ per cent for terrestrial samples (here $^{1}\text{Mg}$ denotes one of the heavier isotopes, i.e., $i = 25$ or 26). Lambert & McWilliam (1986) set a lower limit to $^{1}\text{Mg}/^{24}\text{Mg}$ ($\leq 3$ per cent) for the subgiant $\nu$ Ind with [Fe/H] = -1.52. Barbuy (1985) provides estimates of $^{1}\text{Mg}$ for a
Chemical evolution of the Galaxy

115


In Fig. 10, I show currently available results for \(^{1}\text{Mg}/^{24}\text{Mg}\) versus [Fe/H] in dwarfs and subgiants; the abundance of the neutron-rich isotopes \(^{25}\text{Mg}\) and \(^{26}\text{Mg}\) declines with increasing metal-deficiency, approximately as predicted by theories of stellar nucleosynthesis. The scatter in \(^{1}\text{Mg}/\text{Mg}\) at a given [Fe/H] is probably dominated by observational errors. The decline in \(^{1}\text{Mg}/\text{Mg}\) may begin at a higher metallicity than is evident in the [Na/\alpha] and [Al/\alpha] results. Arnett's (1971) calculations of explosive nucleosynthesis predict the more rapid decline for \(^{1}\text{Mg}/\text{Mg}\); [Na/Mg] and [Al/Mg] drop by about 0.6 dex, but \(^{25}\text{Mg}/^{24}\text{Mg}\) and \(^{26}\text{Mg}/^{24}\text{Mg}\) drop by 2.0 and 1.8 dex respectively as the adopted neutron excess declines by an order of magnitude from the solar value. Woosley & Weaver (1982) predict a qualitatively similar result.

The yield of the odd-even nuclei such as \(^{27}\text{Al}\) is predicted to be controlled by the neutron excess at the site of stellar nucleosynthesis. In explosive nucleosynthesis, the neutron excess is controlled by the \(^{14}\text{N}\) abundance, or the neutron-rich isotopes \(^{18}\text{O}\) and \(^{22}\text{Ne}\) synthesized from \(^{14}\text{N}\), but, thanks to a prior phase of H burning, the internal \(^{14}\text{N}\) (or \(^{18}\text{O}, ^{22}\text{Ne}\)) abundance is set by the sum of the initial C, N, and O abundances. Calculations for massive stars suggest that the effective neutron excess is less strongly tied to the initial composition because of additional processing following the helium-burning phase. However, the predicted yields for Population I and II 25 \(M_{\odot}\) stars differ by about the same amount as Arnett's less realistic calculations of explosive nucleosynthesis (Woosley & Weaver 1982).

Through this tie to the CNO abundances, we may anticipate that the correlation of [Al/Mg] should be tightest when plotted against \(([\text{C + N + O}]/\text{H})\) rather than either [Mg/H] or [Fe/H]; the CNO abundances were calculated from the mean relations for these stars and not the values derived for the individual stars. Of course, one should really employ a weighted mean of the CNO abundances over the several generations of stars prior to the formation of the observed star. The scatter is probably reduced (see Fig. 11 from TLB). (The fact that the scatter is quite obviously larger when [Al/Fe] is plotted against [Fe/H] shows that Al and Fe are synthesized in rather different sites.)

In summary, the variation of odd-even nuclei relative to the \(\alpha\)-nuclei through the disc

![Figure 10](image)

Figure 10. \(^{1}\text{Mg}\) isotopic abundances as a function of [Fe/H]. Observations (here \(^{1}\text{Mg} = ^{25}\text{Mg}\) or \(^{26}\text{Mg}\)) are taken from Barbuy (1985—open circles) and Tomkin & Lambert (1980), Lambert & McWilliam (1986), and McWilliam & Lambert (1986)—solid symbols for the latter three references. The symbol in parentheses is based on a spectrum described as 'bad' by Barbuy.
Figure 11. Aluminium in the halo and disc. The three plots show [Al/Fe] versus [Fe/H] (top), [Al/Mg] versus [Mg/H] (middle), and [Al/Mg] versus [(C + N + O)/H] (bottom). The key to the observations is given in the caption to Fig. 6. Theoretical predictions are by Arnett (1971; lines terminated by A) and Woosley & Weaver (1982; lines terminated by W).

to the halo appears to match rather well the predictions of nucleosynthesis occurring in either explosive or hydrostatic C burning. Abundances of odd-even nuclei (here, Na and Al) in halo stars remain uncertain. To [Fe/H] $\sim -1.5$, recent analyses suggest that our prescription overestimates the Na and Al abundances. Below [Fe/H] $\sim -1.5$, the Na and Al abundances must be considered uncertain. I suspect that they are approximately constant in the extreme halo with a much smaller scatter than is suggested by a casual inspection of Figs 7, 8, and 9. One must not forget persistent reports that Al (and Na) are enhanced in globular cluster ‘CN-strong’ stars.

3. Summary

3.1 Disc-to-Halo Abundance Variations

As a ready guide for the busy theoretician, I present in Figs 12 and 13 my impressions of the mean trends of [el/Fe] (or [el/$\alpha$]) with [Fe/H] for a selection of elements: C, N, and O; the $\alpha$-nuclei (Mg, Si, Ca), the odd-even nuclei (Na, Al—see Fig. 13 where [odd-even/$\alpha$] is given); the light s-process (Sr), the heavy s-process (Ba), and the r-process (Eu). Solid-lines denote those portions of the relations which appear to be well
Figure 12. $[\text{el}/\text{Fe}]$ as a function of $[\text{Fe/H}]$ for C, N, O, $\alpha$-nuclei (Mg, Si, Ca), and $s$- and $r$-process nuclei. Observed trends are represented here by connected straight lines with broken lines denoting uncertainty because the observations are sparse or less accurate.

Figure 13. $[\text{odd-even}/\alpha]$ as a function of $[\text{Fe/H}]$ for Na and Al. See caption for Fig. 12.

determined and exhibit little scatter. Broken lines denote those portions where considerable uncertainty remains as to the mean relation and/or the scatter. The relations are described by linear segments for convenience only. Undue emphasis should not be placed on the fact that most of the relations do not pass through the point
(el/Fe) = 0 and [Fe/H] = 0; as noted above, a thorough scrutiny of potential sources of systematic errors will be necessary before it can be claimed that particular elements are slightly underabundant (e.g., Mg, Si) or slightly overabundant (e.g., C, N) in the Sun relative to a sample of dwarfs of solar metallicity. To complete the crude summary, one should add Ni([Ni/Fe] > 0 for [Fe/H] < −2) and Ti ([Ti/Fe] declines for [Fe/H] < −2)—see LB.

In the variation of [el/Fe] with [Fe/H], a change of slope may occur at up to three metallicities. The most obvious change of slope is that between the disc and halo at [Fe/H] = −1.2 ± 0.1, which is evident in the oxygen and α-nuclei plots, and apparently also in the Na and Al plots. In the disc, there is evidence for a change of slope at [Fe/H] = −0.2 ± 0.1 in the α-nuclei plots. Oxygen may show a change of slope at a slightly higher metallicity, say [Fe/H] = 0.0. In the extreme halo, [Fe/H] ~ −2 marks a change of slope for several elements: carbon, α-nuclei, and, perhaps, the odd-even nuclei (Na and Al), Ti, Ni, as well as the s-process elements. An obvious goal for the future is to examine more stars in the extreme halo in order to define the abundance variations for [Fe/H] ≤ −2.

For Na and Al, [el/α] is plotted because the yields of the odd-even and α-nuclei should be rather closely coupled (see Fig.11 and the accompanying text). As emphasized in Section 2.3, the observational evidence on Na and Al abundances in halo stars is confusing. My suggested trends are weighted heavily towards the results provided by Peterson (1981), Magain (1985), and a few other references providing abundances for just one or two stars each. I assume, too, that the scatter in the Na or Al abundances is small for a given [Fe/H]. GS, and to a lesser degree LB, provide abundances which suggest that my relations in Fig.13 are lower bounds to a distribution which is bounded at the upper end by [odd-even/α] ~ 0.0 for [Fe/H] < −2. The evidence that [Na/α] > [Al/α] in the extreme halo is weak. For [Fe/H] > −1, I show [odd-even/α] to increase with [Fe/H], but the evidence for this is inconclusive; [odd-even/α] ~ 0.0 is an acceptable alternative.

3.2 ‘Primary’ and ‘Secondary’ Elements

In discussions of the chemical evolution of the Galaxy, the labels ‘primary’ or ‘secondary’ are attached to elements. Often, the iron-group elements are taken to be the quintessential ‘primary’ ones; i.e., stellar nucleosynthesis of iron begins with hydrogen as the raw material. Other elements are termed ‘primary’ by the observers when

\[
\frac{\text{el}}{\text{H}} = \frac{\text{Fe}}{\text{H}}, \text{ i.e., } \frac{\text{el}}{\text{Fe}} = 0.
\]

This result follows for simple models of the Galaxy’s chemical evolution when, among several simplifying assumptions, the element (el) may be synthesized from hydrogen with a yield that is approximately a constant fraction of the Fe yield.

An element is labeled ‘secondary’ by observers when

\[
\frac{\text{el}}{\text{Fe}} = \frac{\text{Fe}}{\text{H}}.
\]
Chemical evolution of the Galaxy

In the simple models, this relation follows when the element cannot be synthesized from hydrogen, but from a heavier element which was synthesized in earlier generations of stars.

Nitrogen is perhaps most frequently cited as an example of a secondary element. (It may also be synthesized as a primary element.) 'Secondary' because $^{14}$N, the dominant isotope, is synthesized in H burning within a star when the CNO-cycles converts existing $^{12}$C to $^{14}$N, and, also, $^{16}$O to $^{14}$N in the deeper hotter layers. In many stars, this $^{14}$N may be ejected into the interstellar medium with a yield which depends on the C abundance of the star as its formation. With the assumption that C is primary ([C/Fe] ~ 0), simple models predict

$$\frac{N}{Fe} = \frac{Fe}{H}.$$  

Stars may synthesize $^{12}$C from H when H burning is followed by He burning with $^{12}$C as the principal product. If some of this $^{12}$C is exposed to H burning, the resultant $^{14}$N is a 'primary' product and, if several simple assumptions are valid, one may expect $[N/Fe] = 0$.

Inspection of Fig. 12 shows that

$$\frac{N}{Fe} \sim \frac{N}{C} \sim 0$$  

and

$$\frac{N}{O} \leq \frac{O}{H}$$

for nitrogen in disc stars. The first relations suggest that N is a 'primary' element relative to C, Fe, and many other elements showing $[el/Fe] \sim 0$. Two sites for primary production of N were discussed by Bessell & Norris (1982): (i) AGB stars in which fresh C is converted to N by hot protons; (ii) very massive (\sim 500 M_\odot) stars.

The second relation suggests that N is a 'secondary' element relative to O. If existing O (and C) were converted to N by hot proton in significant amounts within a star and this processed material were ejected, this relation might be explained. No stellar models satisfy these requirements. Earlier, we (Tomkin & Lambert 1984) suggested that N is in fact primary, and this second relation is simply a numerical accident resulting from combining $[O/H] \sim 0.5$ $[Fe/H]$ and $[N/Fe] \sim 0$.

This last discussion shows that a classification of elements as 'primary' or 'secondary' must involve more than the inspection of plots of $[el/Fe]$ versus $[Fe/H]$. The puzzling case of the s-process elements (Tinsley 1979) provides a second example. The s-process elements in the disc would appear to be 'primary' elements (see Fig. 12). If we were to prefer oxygen as the 'primary' reference element, we note that

$$\frac{s}{O} = \frac{O}{H}$$

for disc stars and, perhaps, most of the halo stars; i.e., the s-process elements should now be referred to as 'secondary'. Moreover, one can offer a plausible nucleosynthetic origin for this relation.

The production site of the s-process elements with 70 < A < 204 is believed to be the convective shells of thermally pulsing intermediate-mass stars on the asymptotic giant branch (Iben & Truran 1978). The predicted yields show that a solar abundance pattern is produced. The source of neutrons for the s-processing is predicted to be the $^{22}$Ne(α,n)$^{25}$Mg reaction, where the $^{22}$Ne is synthesized by the chain

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$^{14}\text{N}(x,\gamma)^{18}\text{F}(\beta^+,\gamma)^{18}\text{O}(x,\gamma)^{22}\text{Ne}$, and the $^{14}\text{N}$ is produced during H burning by CNO cycling of the initial CNO nuclei. The neutron supply is thus proportional to the sum of the initial CNO abundances. If the neutron supply is the factor that limits the production of s-process elements—inspection of Truran & Iben's (1977) results suggests that it is—the s-process yield will also be proportional to the sum of the initial CNO abundances (in effect, the O abundance because the O abundance dominates). It is therefore more instructive to consider [s/O] rather than [s/Fe]. In the absence of infall of metal-poor gas, standard relations predict

$$
\begin{bmatrix}
\text{s} \\
\text{O}
\end{bmatrix} = \begin{bmatrix}
\text{O} \\
\text{H}
\end{bmatrix}.
$$

This is, in fact, the observed relation for [Fe/H] > −1.5 (see above and Fig. 12).

A third example of possible dual assignment of 'primary' and 'secondary' is Na or Al where [Na/Fe] ∼ [Al/Fe] ∼ 0 with considerable scatter, a result earning Na and Al the label 'primary'. But as we showed with Fig. 11, [Na/Mg] and [Al/Mg] are better correlated with [(C + N + O)/H] which is a stand-in for the neutron excess in the C-burning zones in which Na and Al are predominantly 'secondary' products.

I urge care in the christening of elements as 'primary' and 'secondary'!

For the extreme halo stars, Truran (1981) suggested that the r-process dominates production, and detailed abundance analyses (Sneden & Parthasarathy 1983; Sneden & Pilachowski 1985) indeed find that the r-process—not the s-process—can account for the relative abundances. This cannot be the complete story, because whether the r-or s-process (or both) are effective, the observed abundances of Sr, Ba, and many other heavy elements decline in the extreme halo relative to Fe and Eu (an r-process element). Some variable factor is needed (e.g., the pattern of r-process yields must vary with metallicity) or, as Magain (1985) notes, [s/Fe] would have constant negative value in the halo (the limited observations do not yet exclude this possibility for [Fe/H] < −2.5). The stars examined in detail by Sneden and colleagues have [Fe/H] = −2.6 and −2.3. Before the metallicity of the disc was reached, the s-process must have begun to dominate.

In these last paragraphs, I have apparently strayed from my terms of reference. My excuse is that the nucleosynthesis of the elements from the light to the heavy are linked and, hence, the full understanding of their nucleosynthesis may come only when observers and theoreticians recognize the elements as an ensemble. My principal goal in preparing this review will have been met if a few observers are stimulated to go to a telescope with an observing program designed to address the glaring deficiencies in our knowledge of the abundances of the light (and other) elements.

Acknowledgements

I thank Drs P. François, P. E. Nissen, and C. Sneden for providing important results in advance of publication. My research on the light elements is supported in part by the U.S. National Science Foundation (grant AST 83-16635) and the Robert A. Welch Foundation.
Chemical evolution of the Galaxy

References

Note added in proof

Of the several significant developments since my talk in New Delhi in December 1985, two should be noted:

(i) The extensive study by Gratton & Sneden will appear in a slightly revised form as two papers in Astronomy and Astrophysics. Relative to the preliminary results discussed in my review, the revisions conform in the main to my suggested trends (Figs 12 and 13), but the scatter about those trends is reduced significantly. One particular new result deserves emphasis. Gratton & Sneden now show that potassium behaves like the $\alpha$-elements Mg, Si, and Ca; i.e., $[\text{K/Fe}]$ increases with decreasing metallicity to reach $[\text{K/Fe}] \sim 0.4$ for $[\text{Fe/H}] < -1$. Potassium with stable isotopes $^{39}\text{K}$ and $^{41}\text{K}$ might have been expected to have followed the other odd-even nuclei in showing a lower abundance (relative to either Mg or Fe) in halo stars. Potassium's differing nucleosynthetic behaviour may be a clue to the origin of the Na and Al enrichments reported for some stars in certain globular clusters. If the strengthening of Na I and Al I lines in these stars is due to a change of atmospheric structure, the K I resonance lines at 7664 and 7699 Å might be expected to show a similar strengthening. On the other hand, if the Na and Al enrichments are real and produced by the same nucleosynthetic process responsible for the overall enrichment in the Galaxy, one would not expect K enrichments in the Na and Al enriched globular cluster stars.

(ii) Magain (1987, Astr. Astrophys., in press) provides abundances of $\alpha$(Mg, Si, Ca) and odd-even (Na, Al) elements "on the basis of literature data reanalysed in an homogeneous way". His results generally confirm my suggested trends. For the $\alpha$-elements, the mean abundances for this sample in which all stars belong to the halo (the most metal-rich star has $[\text{Fe/H}] = -0.87$) are $[\text{Mg/Fe}] = 0.43 \pm 0.02$ (17 stars), $[\text{Si/Fe}] = 0.39 \pm 0.05$ (8 stars), and $[\text{Ca/Fe}] = +0.50 \pm 0.04$ (14 stars). The mean values do not differ sensibly when the sample is divided at $[\text{Fe/H}] = -2$. Gratton & Sneden's sample of 13 extremely metal-poor stars $([\text{Fe/H}] \leq -1.3)$ yields the following mean values: $[\text{Mg/Fe}] = 0.34 \pm 0.03$, $[\text{Si/Fe}] = 0.50 \pm 0.06$, and $[\text{Ca/Fe}] = 0.31 \pm 0.09$. (I give the formal errors of the mean values.) Magain's reanalysis of published data suggests that the $\alpha$-elements (relative to Fe) are slightly more abundant than any recommended trend would suggest, and confirms my suggestion that the scatter in $[\text{el/Fe}]$ about the mean value is very small, even in the halo; Magain's sample is concentrated between about $-1.5$ to $-2.5$ in $[\text{Fe/H}]$. More importantly, his results do not support my tentative suggestion that $[\alpha/\text{Fe}]$ may increase again in the extreme halo ($[\text{Fe/H}] < -2$).

The few stars which pass Magain's stringent selection criteria show the decline of $[\text{Al/Mg}]$ with declining $[\text{Mg/H}]$ to be similar to that indicated by Fig. 11 and the combination of Figs 12 and 13.

Past and Present Metal Abundance Gradient in the Galactic Disc

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Abstract. A critical discussion of some determinations of metal abundance gradient in the galactic disc is presented with an attempt to homogenize the results related to local and large-scale gradients. A new estimation of the palaeogradient in intermediate and old disc population is presented. The gradient is found to depend on galactocentric distance, and to be nearly constant with time during the lifetime of the galactic disc.

Key words: Galaxy, metal abundance gradient

1. Introduction

Several reviews have been dedicated to the topic of abundance gradient in the galactic disc (see Pagel 1975; Peimbert 1974, 1977, 1979; Janes 1979; and more recent work of Luck 1982; Shaver et al. 1983 for the abundances in the interstellar matter).

A wide variety of objects have been used for gradient determinations: the nearby stars, the G and K giants, the F stars (for the local gradient $\delta [M/H]/\delta r$ at $r_\odot$, the solar galactocentric distance), the yellow supergiants and the Cepheids, the open clusters, the H II regions, the planetary nebulae etc. for abundance estimates in situ at large distances.

Selected values of abundance gradients deduced from stellar samples are given in Table 1. They refer to young, intermediate, old, or mixed stellar populations. The extreme values range between 0.00 and $-0.13$ kpc$^{-1}$. The various approaches differ by the techniques used and the observational material, the sampling conditions, the basic assumptions and the volume of space investigated.

Part of differences between gradients deduced from in situ observations and those obtained from kinematical considerations originates in the adopted solar galactocentric distance and are reduced when the recommended value $\varpi_\odot = 8.5$ kpc is adopted. The gradients by Janes & McClure (1972), Grenon (1972, 1977), Mayor (1976) have then to be multiplied by a factor 1.18; a factor of the same order has to be applied to gradients from H II regions with distance deduced from rotation curve assuming $\varpi_\odot = 10$ kpc. In the following, $\varpi_\odot = 8.5$ kpc will be assumed.

Observations in situ are clearly to be preferred for the young disc objects as they allow both a gradient determination independent of any dynamical models of the Galaxy, the galactocentric distances being relative to that of the Sun, and a detailed picture of the abundance distribution as a function of the distance to the galactic centre.

As the [N/Fe] ratio in stars appears independent of [Fe/H] for a wide range of [Fe/H], at least those typical of the galactic disc (cf. Matteucci & Tornambe 1985), the [N/H] ratio deduced from H II regions may be used as an additional estimator of
Table 1. Metal abundance gradient determinations based on stellar observations

<table>
<thead>
<tr>
<th>Object</th>
<th>Age</th>
<th>Parameter</th>
<th>$\delta p/\delta\varpi$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>gG-gK</td>
<td>mixed</td>
<td>[CN/H]</td>
<td>-0.02</td>
<td>Janes &amp; McClure 1972</td>
</tr>
<tr>
<td>dG-dK</td>
<td>mixed</td>
<td>[M/H]</td>
<td>-0.05</td>
<td>Grenon 1972</td>
</tr>
<tr>
<td>dF</td>
<td>young to intermediate</td>
<td>[M/H]</td>
<td>-0.00</td>
<td>Clegg &amp; Bell 1973</td>
</tr>
<tr>
<td>gG-gK</td>
<td>mixed</td>
<td>[M/H]</td>
<td>0.0</td>
<td>Jennens &amp; Helfer 1975</td>
</tr>
<tr>
<td>dF-dG</td>
<td>young</td>
<td>[M/H]</td>
<td>-0.10</td>
<td>Mayor 1976</td>
</tr>
<tr>
<td></td>
<td>old</td>
<td>[M/H]</td>
<td>-0.05</td>
<td>Mayor 1976</td>
</tr>
<tr>
<td>G-K</td>
<td>old</td>
<td>[M/H]</td>
<td>-0.07</td>
<td>Grenon 1977</td>
</tr>
<tr>
<td>gG-gK</td>
<td>intermediate</td>
<td>[CN/H]</td>
<td>-0.05</td>
<td>Janes 1979</td>
</tr>
<tr>
<td>open</td>
<td>young</td>
<td>[Z/X]</td>
<td>-0.095</td>
<td>Panagia &amp; Tosi 1981</td>
</tr>
<tr>
<td>clusters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cepheids</td>
<td>young</td>
<td>[M/H]</td>
<td>-0.07</td>
<td>Harris 1981</td>
</tr>
<tr>
<td>G-K 1b</td>
<td>young</td>
<td>[Fe/H]</td>
<td>-0.13</td>
<td>Luck 1982</td>
</tr>
</tbody>
</table>

Metallicity at large distances from the Sun. Various [N/H] gradients are summarized in Table 2. They are steeper than $[M/H]$ gradients deduced from stars; typically $\delta[N/H]/\delta\varpi = -0.15$ kpc$^{-1}$.

Planetary nebulae abundances, intermediate between those of the local interstellar medium and those of the stellar ejecta, will not be discussed here as their ages and birthplaces of their progenitors are difficult to determine.

All abundance gradient determinations are highly sensitive to the distance scale adopted, to the possible coupling between luminosity and metallicity, to the sampling and its possible dependence on age and/or abundance.

In the following sections we will attempt to produce a global picture of the radial metal abundance distribution in our Galaxy, at the present time and in the past. This tentatively uses the published data after discussion and homogenization and also uses new observational material.

Table 2. Nitrogen abundance gradient in interstellar medium.

<table>
<thead>
<tr>
<th>Objects</th>
<th>$\delta[N/H]/\delta\varpi$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>H II regions</td>
<td>-0.10</td>
<td>Hawley 1978</td>
</tr>
<tr>
<td></td>
<td>-0.14</td>
<td>Peimbert 1979</td>
</tr>
<tr>
<td></td>
<td>-0.08</td>
<td>Talent &amp; Dufour 1979</td>
</tr>
<tr>
<td></td>
<td>-0.23</td>
<td>Peimbert, Torres-Peimbert &amp; Rayo 1978</td>
</tr>
<tr>
<td>Planetary nebula</td>
<td>-0.13</td>
<td>d'Odorico et al. 1976</td>
</tr>
<tr>
<td></td>
<td>-0.18</td>
<td>Torres-Peimbert &amp; Peimbert 1977</td>
</tr>
<tr>
<td></td>
<td>-0.27</td>
<td>Peimbert &amp; Serrano 1980</td>
</tr>
<tr>
<td>Supernovae</td>
<td></td>
<td></td>
</tr>
<tr>
<td>remnants</td>
<td>-0.095</td>
<td>Binette et al. 1982</td>
</tr>
</tbody>
</table>
Galactic metal abundance gradient

2. The definition of stellar samples

The reliability of a gradient, defined for a given epoch and galactocentric distance, is conditioned by the quality of the stellar or nonstellar sample used and by the validity of the methods applied to the gradient determination. The constitution of an unbiased sample is indeed a nontrivial process as most of relations between the physical, the photometric and the spectroscopic parameters defined for objects in the solar vicinity are generally no longer valid at large distances where the metal abundances are expected to be significantly different. In the solar neighbourhood itself, abundance effects on the stellar classification and also evolutionary effects may lead to serious biases. In the case of a stellar sample, the following conditions must be verified:

1. The stellar ages should be known either from their evolutionary stage, or at least from the kinematical properties. A mixing of ages leads to a flattening of the gradient (cf. Section 5). Problems arise with the red giants and the G and K dwarfs.
2. The metal abundance estimator should not show residual effects of temperature or reddening. If it does, we may expect spurious dependence of the metallicity on the age in the first case and a bending of the relation \([M/H]\) versus \(\varpi\) in the second.
3. The objects should be situated at the same galactocentric distances as they had at the time of their formation. If not, the galactocentric distances of their birthsites have to be evaluated. All objects more than a few billion years old are problematic in this respect.
4. The sample itself should not be biased in favour of particular abundances or ages. Rather surprisingly, this last condition is almost never verified and most selection criteria are more or less dependent on metallicity and age. As an example, a selection of F-type stars excludes practically all old metal-rich stars (cf. Section 7).

3. Large-scale gradient in the young disc

The modelling of the galactic chemical evolution requires a knowledge of the metal abundance distribution over the whole range of galactocentric distances. Most determinations of gradient are defined over a small range of distances—typically \(\varpi_\odot \pm 2\) kpc.

At large distances the information on the metallicity distribution relies mainly on the galactic clusters, the bright yellow and red supergiants (Cepheids included), and on the C, N, O abundances in \(\text{HII}\) regions.

3.1 Open Clusters

The intermediate-age open clusters have several unique advantages for the gradient determination. Their HR diagrams allow a precise estimation of their evolutionary age, typically 0.5 to 3 billion years. The luminosity of red giants in core He-burning phase is almost invariant with the age and metal abundance (cf. Cannon 1970). Clump stars are probably the best distance estimators in the Galaxy. The number of red giants is generally sufficient for an accurate evaluation of the mean metallicity of each cluster.

The pioneering investigation by Janes (1979) using DDO photometry of 41 clusters...
indicates a gradient $\delta[\text{CN/H}] / \delta \varpi = -0.05 \text{kpc}^{-1}$ when the clusters data were combined with those of field K giants observed towards the galactic centre and anticentre in order to extend the range of galactocentric distances.

Returning to the original data we see (Fig. 1) that the abundances in clusters show a marked dependence on $\varpi$ although some scatter is present. This scatter exceeds the dispersion in abundances observed in young populations in the solar vicinity. In addition to the uncertainties due to measurement errors and reddening corrections, the factors contributing to the observed scatter are the dispersion in the abundances in the interstellar medium at a given galactocentric distance and the fact that old clusters would have moved away from their birthsites by several kiloparsecs in the radial direction. (see e.g. the galactic orbits computed for M67 and NGC 188 by Keenan, Innanen & House 1973). The mean gradient is however not significantly altered by this uncertainty on the birth-distances: It appears to be constant over 6 kpc, from $\varpi - 1.7$ to $\varpi + 4.2$ kpc with a mean value of $\delta[\text{CN/H}] / \delta \varpi = -0.11 \text{kpc}^{-1}$.

![Figure 1](image_url)

Figure 1. (a) The distribution of metal abundances of open clusters deduced from CN parameter by Janes (1979), and (b) the mean abundance distribution of clusters (solid line) and of clusters plus field giants (dashed line). In panel (a) the horizontal line shows the amplitude of epicyclical motion of M67 according to Keenan (1973).
The inclusion of field stars with uncertain distances, apparently overestimated, leads to a flattening of the abundance distribution which is more pronounced towards the galactic centre. The gradient from the clusters appears to be the most reliable for intermediate-age population in the range of ages $0.5 \times 10^9$ to about $4 \times 10^9$ yr.

Intermediate-age to old open clusters are not identified at distances exceeding 2 kpc towards the galactic centre, probably a consequence of their shorter lifetimes in the regions where tidal evaporation becomes intense. Other metal abundance indicators have then to be used for the inner disc and bulge populations.

### 3.2 Supergiants

Supergiants with ages much smaller than that of the galactic disc are excellent tracers of the present abundance distribution in the interstellar matter. The F to M supergiant spectra show a sufficient number of spectral features usable as abundance estimators or even allow direct $[\text{Fe}/\text{H}]$ determinations through high-dispersion analysis. Their intrinsic brightness allows $[\text{M}/\text{H}]$ determinations at very large distances from the Sun.

Cepheids form a subset with the advantages of detection, even in crowded areas, and the accuracy of their absolute luminosities. They have been used by Harris (1981) for a determination of abundance gradient. The distribution of $[\text{M}/\text{H}]$ as a function of $v$.

![Diagram](image)

**Figure 2.** Mean metal abundances of classical Cepheids (dots; Harris 1981) and of F–M supergiants (Luck 1982; squares).
appears somewhat irregular (cf. Fig. 2), with some flattening between 6.5 to 9.5 kpc, a steep increase towards the galactic centre and a slope of $-0.11$ kpc$^{-1}$ outside 10 kpc, the mean gradient being about $-0.07$ kpc$^{-1}$.

A spectroscopic investigation of non-variable F to M supergiants by Luck (1982) leads to a steeper local gradient of $-0.13$ kpc$^{-1}$ over 2.5 kpc, in conflict with the results of Harris. In both the cases, the star samples have essentially the same ages and should have shown similar abundance distribution. As several supergiants are members of stellar associations with well-defined distances, Luck’s distance scale is not questionable. But as mentioned by the author, some uncertainty remains concerning the metallicity of M supergiants. As a matter of fact, when [Fe/H] values are plotted as a function of spectral type, a systematic trend exists at given galactocentric distance, in the sense that cooler stars appear more metal deficient. As the ratio of K-M to F-G supergiants increases towards the anticentre, this effect leads to an overestimation of the gradient. If tentatively we correct the [Fe/H] ratios by $+0.05$, $+0.11$ and $+0.23$ for K0, K5, M0 stars respectively, the gradient becomes $\delta[Fe/H]/\delta m = -0.09$ kpc$^{-1}$ with a mean [Fe/H] ratio at solar galactocentric distance $= +0.095$. Although the zero point of the [Fe/H] scale remains somewhat uncertain, this local ratio is consistent with that observed in young stellar groups indicating that the mean abundances in newly formed stars do not exceed 0.1 dex with respect to that of the Sun.

When compared with the [N/H] distribution (cf. Section 3.3) or with the cluster abundances, the distribution derived by Harris appears excessively metal-rich at large galactocentric distances. Several sources of uncertainty are present and complicate the interpretation of this distribution. One might suspect that the luminosities of short-period Cepheids on which the abundances beyond 13 kpc are primarily based could have been overestimated (cf. Schmidt 1980). In order to check this point, the period-luminosity relation of SMC Cepheids has been used as their [$M$/H] are similar to that expected in the galactocentric distance interval 13 to 15 kpc, assuming a distance modulus of 18.5 for SMC. The gradient then becomes only slightly steeper, i.e. $-0.13$ to $-0.14$ kpc$^{-1}$ between 11 and 16 kpc, leading to $A = \frac{1}{4} A_\odot$ at $\pi = 15$ kpc.

The most critical point is the effect of the variation of the reddening law with the galactocentric distance. We may expect the galactic interstellar matter to behave similarly to that of M 31 where the ultraviolet extinction increases with galactocentric distance for a given $E(B-V)$ excess. At $\pi = 13$–14 kpc, the reddening law could be close to that observed in SMC by Lequeux et al. (1984), and at $\pi = 10$–11 kpc close to that found in LMC by Nandy et al. (1980), if the CNO abundances in the outer parts of the Galaxy vary in a similar way as in Magellanic clouds. With a steeper extinction in the ultraviolet Harris’ metallicity parameter overestimates the metal abundance at a rate increasing with the gas metal-deficiency and then with the distance. Harris’ (1981) distribution should then be considered as an upper limit outside the solar circle. The steepening towards the galactic centre seems to result mainly from the choice of [$M$/H] = +0.3 (Luck 1979) for the most metal-rich Cepheids, a value revised downwards since (Luck 1982).

The difficulties pointed out here are not specific to the photometric system employed, but affect all determinations of abundances based on violet or ultraviolet excess measured with intermediate or broadband filters. The stellar distances themselves are not totally reliable as there is some evidence that the ratio $R = A_\nu/E(B-V)$ is also dependent on the gas metal content (see e.g. Fitzpatrick 1985).
3.3 Interstellar Matter

A discussion of the elemental abundance gradients in the interstellar matter is beyond the scope of this paper. Nevertheless, abundances observed in H II regions are extremely useful as they complete our knowledge on abundance distribution at short galactocentric distances and they may be used as a check of abundances derived from young stars. In the range of metallicities occurring in the portion of the disc investigated until now (+0.5 > [M/H] > −1.0), the nitrogen abundance is expected to follow that of the iron peak elements (cf. Matteucci 1986). For a comparison with the metallicity gradients we will adopt [N/H] = [M/H].

C, N, O, and He abundance gradients were discussed by Peimbert (1979). The oxygen and nitrogen gradients were −0.10 kpc⁻¹ in the distance range 8 to 14 kpc assuming w☉ = 10 kpc. More recently, Shaver et al. (1983) derived abundances from electron temperatures over a wider range of galactocentric distances (cf. Fig. 3). The distances to H II regions were obtained from radial velocities using the Schmidt (1965) rotation curve with w☉ = 10 kpc. The derived oxygen and nitrogen gradients are −0.07 ± 0.015 and −0.09 ± 0.015 kpc⁻¹ respectively. With the Sun at 8.5 kpc, the nitrogen gradient would be −0.105 ± 0.02, but this value appears quite dependent on the models of galactic potential adopted. When the distances are deduced from Schmidt (1965) rotation curve the gradient tends to steepen slightly outside the solar circle, and the [N/H] distribution fits almost perfectly those of open clusters and supergiants (cf. Fig. 4). As the Schmidt curve is known to be somewhat unsatisfactory at large

![Graph showing abundance distribution](image)

Figure 3. The nitrogen abundance distribution adopted from Shaver et al. (1983). Symbols: ▲ lower limits; p: peculiar H II regions. The galactocentric distances are deduced from a Sc-like rotation curve by Bahcall et al. (1982). The mean sequence is given in full line. The dashed sequence is that obtained with Schmidt (1965) rotation curve.
galactocentric distances, it may be tempting to re-evaluate the gradient using the Bahcall et al. (1982) rotation curve, which is flat in the region 40–60 kpc and is similar to those observed in Sc galaxies. As the kinematical distances are increased, especially at large \( \varpi \), the gradient becomes more nearly constant, and also smaller, i.e. \(-0.066\) kpc\(^{-1}\) over 8 kpc. This value is inconsistent with that deduced from stars with well-known distances. The agreement with Harris’ distribution (Fig. 4) may be considered as partially spurious remembering the reservation on the validity of photometric abundances.

An additional evidence for a gradient of about \(-0.10\) dex kpc\(^{-1}\) at \( \varpi_\odot \) is provided by the distribution of abundances in supernovae remnants. Binette et al. (1982) found a nitrogen gradient of \(-0.103\pm0.03\) or \(-0.087\pm0.03\) (if the nitrogen is primary or secondary, respectively), the mean value \(-0.095\pm0.03\) being a suitable value to adopt.

4. Old disc stars: birthplaces and ages

The basic difficulty with old stars is the fact that—since these stars follow non-circular orbits—they are presently observed at galactocentric distances which are often different from those at the time of their birth. This is a consequence of both their initial space motions and of the diffusion of their orbits with time.

The effects of isotropic diffusion of the stellar orbits have been investigated by Wielen (1977) and more recently by Wielen & Fuchs (1985). Although the origin of this
diffusion is not fully explained, a semi-empirical approach shows that the amplitude of epicyclical motions increases as $t^4$. After a few billion years (cf. Fig. 5), the star's galactocentric distance may differ by several kpc from its initial value whereas the mean galactocentric distance $\bar{\sigma} = \frac{1}{2} (R_s + R_p)$, the mean between apo- and pericentric distances, remains fairly close to the initial value $\sigma_i$.

In order to derive an abundance gradient in the disc at a given epoch in the past, it is then necessary to replace each star or object at its right initial galactocentric distance, and hence to define their galactic orbits.

The necessary ingredients are evidently the distances, the proper motions, and the radial velocities. The need on significant proper motions restricts the volume of investigation to a few hundred parsecs from the Sun.

As the solar vicinity is visited by stars showing a wide variety of orbits, eccentricities, and mean galactocentric distances, it is possible to trace back in the past the distribution of $[M/H]$ as a function of $\sigma$ provided that some discrimination on age is made. Mayor (1976) has shown that an age criterion is necessary for decoupling the effects of a gradient at a given epoch and of the metal enhancement with time at a given galactocentric distance.

Except for subgiants and for a few main-sequence stars for which Ca II K line intensities are known, no individual stellar ages are available. Especially for the oldest populations, the number of stars with known ages is clearly insufficient for a statistically accurate determination of palaeogradients of abundances. We have then to rely on kinematical age estimators.

The space velocities dispersions $\sigma_\mu, \sigma_\nu, \sigma_w$ are known to be increasing functions of age. A calibration of $\sigma$, versus age has been worked out by Mayor (1976).

An age ranking using orbit eccentricities has been frequently used in the past. For small-eccentricity stellar samples, part of the spread in age and abundance results from the inclusion of stars with non-negligible perpendicular motions (or orbital inclinations). It is possible to refine the age ranking by taking into account not only the

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**Figure 5.** Example of diffusion orbit from Wieland (1977). The thick line shows the variation of the mean distance to the centre $\bar{\sigma}$ as a function of the age.
M. Grenon

eccentricity but also the \( W \) velocity component, which is a sensitive function of age. The following function will be used here for the constitution of groups of kinematical ages:

\[
f = \frac{1}{C} \left[ \frac{(U_c)^2}{\sigma_u} + \frac{(V_c)^2}{\sigma_v} + \frac{(W_c)^2}{\sigma_w} \right]^{1/2}
\]

with \( U_c = U - 10, \ V_c = V + 6, \ W_c = W + 6 \), and \( U, V, W \) the velocity components relative to the Sun. The values \( \sigma_u, \sigma_v, \sigma_w \) were equal to those observed by Vyssotsky in an unbiased sample of dK–dM stars. The constant \( C \) is adapted in such a way that for \( W_c = 0 \), and for small eccentricities \( e \), \( f = e \). The \( f \) function becomes:

\[
f = (1/300)(U_c^2 + 2.5 V_c^2 + 3.5 W_c^2)^{1/2}.
\]

An \( f \) value exceeding a given threshold \( f_0 \) is a sufficient condition for an age \( a > a_0 \), but as for the eccentricity, it is not a necessary condition and a partial mixing of ages is then unavoidable especially for small \( f \) samples.

An age grouping according to \( f \) parameter (or \( e \)) makes the implicit hypothesis that stars sharing the same \( f \) value should have the same age whatever their birth-distance could be. This assumption would be correct only if the mechanism of diffusion of orbits would have the same efficiency at all the galactocentric distances. It is probably not true as regards the perturbations by molecular clouds whose density shows a strong dependence on \( \varpi \). We may suspect that stars at \( \varpi < \varpi_\odot \) are somewhat younger than those at \( \varpi > \varpi_\odot \) for a given value of \( f \).

The orbital parameters \( R_u, R_v, \vec{\varpi} \) are deduced from space velocities with the help of a galactic potential model. The model adopted here was built by P. Magnenet (personal communication, 1984) and fits the second Sc-like rotation curve by Bahcall et al. (1982). It is a three-component model assuming \( \varpi_\odot = 8.0 \) kpc, a circular velocity at the Sun equal to 228.7 km s\(^{-1}\) and a local density 0.15 \( M_\odot \) pc\(^{-3}\). The implications of this particular choice will be discussed in the next section.

The derivation of abundance gradients from distributions of [\( M/H \)] versus \( \varpi \) also assumes the conservation of \( \vec{\varpi} \) with time. This hypothesis is approximately true as regards the diffusion of the orbits but not as concerns the effect of a variation of the galactic potential consecutive to the slow building up of the disc. The non-conservation of \( \vec{\varpi} \) for the oldest stars will affect the gradient value less than that of the mean [\( M/H \)] ratio as a function of time at \( \varpi_\odot \), in the interval of \( \varpi = 7 \) to 12 kpc covered by the present investigation.

5. The NLTT sample

Stars from Luyten’s NLTT catalogue with \( m_B \leq 11.5 \) belonging to the declination zone \(+10^\circ \) to \(-10^\circ\) have been observed photometrically in the Geneva system from La Silla, Chile, and partly with Coravel, from Haute Provence Observatory, for radial velocities.

This sample, with proper motions exceeding 0.19 arcsec yr\(^{-1}\), is tangential-velocity limited, \( e.g. \ V_T \leq 90 \) km s\(^{-1}\) at 100 pc, but not directly metal abundance biased. It consists of a mixture of nearby stars, old disc and halo stars.

The stellar physical parameters are deduced from calibrations of Geneva system for late-type stars by Grenon (1978, 1981). Stars cooler than about K4 V are not considered here as no reliable [\( M/H \)] estimator is available. Spatial velocities and
metal abundances have been obtained for 530 stars in the range of distances 20 to 100 pc. The stars closer than 20 pc will be considered separately as nearby stars.

When stars are divided in intervals according to \( f \) parameter, we obtain, (cf. Fig. 6) the following abundance distributions: for \( f < 0.2 \) we see a unimodal distribution centred on \([M/H]=0\), and similar to that of unevolved nearby G and K stars (Grenon 1984).

The interval \( 0.3 < f < 0.5 \) is characterized by the presence of a bimodal distribution, showing a mild metal poor, and a metal-rich to SMR populations. The mode of the \([M/H]\) distribution is shifted towards low \([M/H]\) with increasing \( f \) values showing a smooth transition from population I to II stars. The metallicity distribution of stars with \( f \geq 1 \) is essentially the same as that of globular cluster system.

Fig. 7 shows the distribution of \([M/H]\) versus \( \bar{\omega} \). A general increase of the mean \([M/H]\) with decreasing \( f \) is patent but also that of the mean \( \bar{\omega} \) with \([M/H]\). The vast majority of old stars have \( \bar{\omega} \) smaller than \( \bar{\omega}_\odot \). Neglecting the age separation would lead to an almost zero gradient in the interval \( 6 < \bar{\omega} < 9 \) kpc.

When stars with \([M/H] > 0.0 \) are considered, the mean metallicity increases with decreasing \( \bar{\omega} \), a consequence of the metallicity gradient. As the stars with the smallest \( \bar{\omega} \) and the highest \([M/H]\) are also the oldest, we could deduce that the metallicity has decreased with the time if we neglect to take into account the stellar birthplaces.

The mean \([M/H]\) are plotted as a function of \( \bar{\omega} \) in Fig. 8a for three intervals of \( f \). The group defined by \( f \leq 0.20 \) contains young to intermediate age stars, typically less than 3

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**Figure 6.** Metal abundance distributions of NLTT stars hotter than K4 V for various \( f \) parameter intervals. The Hyades \([M/H]\) is \(+0.15\).
to 4 billion years old; the interval 0.20 to 0.35 correspond to ages of about 3–10 \times 10^9 yr and the interval 0.35 to 0.70 to ages exceeding 10^{10} yr. The striking feature is that, for the first two age groups, the $[M/H]$ distribution is essentially the same in the domain of overlap, indicating a very small (if any), metal abundance enrichment during the galactic disc lifetime. At $\omega_\odot$ the oldest group is only 0.10 dex, more metal poor than the young stars which indicate $[M/H]_{\odot} = -0.07$. The flattening of the gradient for $\omega < 7.5$ kpc, or even the decrease of $[M/H]$ for the oldest group, is a spurious effect. For large eccentricities and small $\omega$, it appears no more possible to discriminate between inner spheroid and old disc stars on the basis of the kinematical criterion alone. The minimum $\omega$ for SMR stars is about 6.2 kpc (Fig. 7). At smaller $\omega$, the velocity dispersion of disc stars is then not large enough to produce a significant fraction of orbits with apocentric distances $\geq \omega_\odot$. For $\omega$ less than about 7.5 kpc, the number of SMRs (the high eccentricity fraction of inner old-disc stars) becomes small compared to that of intermediate population stars characterized by a higher velocity dispersion and a lower metallicity. In this range of galactocentric distances the mean $[M/H]$ is not appropriate to describe the disc metallicity and underestimates it. The NLTT stars show a gradient of $-0.07$ kpc$^{-1}$ for $\omega$ from 7.0 to 8.7 kpc and $-0.14$ kpc$^{-1}$ for $\omega$ from 8.7 to 10 kpc.
Figure 8. The distribution of the mean metal abundance $[M/H]$ as a function of $\bar{\mu}$. Symbols: $\bullet : f \in [0.0, 0.20]$; $\blacksquare : f \in [0.21, 0.35]$; $\triangle : f > 0.35$. (a) Gliese's stars with $r < 20$ pc; (b) NLTT stars with $r$ from 20 to 80 pc; (c) all stars; open symbols: Bahcall et al. (1982) rotation curve; full symbols: Eggen, Lynden-Bell & Sandage (1962) potential.
6. The stars nearer than 20 pc

The NLTT sample being kinematically biased, it is important to check the results using stars with known proper motion in a distance-limited sample. Gliese's catalogue is believed to be fairly complete down to at least K5 V, and may be considered as a sample complete in volume.

For 648 stars with known radial velocities, photometric $[M/H]$ and distances confirmed to be less than 20 pc, orbital parameters are computed in the same way as for stars with known proper motions. For groups with $f \leq 0.35$, $[M/H]$ versus $\bar{\sigma}$ distribution appears to be essentially the same as for the NLTT sample (Fig. 8b). The number of stars with $f > 0.35$ is insufficient here for a description of the trend of $[M/H]$ versus $\bar{\sigma}$. The change of slope at $\bar{\sigma} = 8.7$ kpc is apparent here too and the gradient outside 8.7 kpc is again $-0.14$ kpc$^{-1}$, independent of age. The amplitude of this change appears to be quite sensitive to the shape of the galactic potential in the outer regions.

When the Eggen, Lynden-Bell & Sandage (1962) potential is adopted, this curvature almost vanishes (Fig. 8c). The condition that gradients deduced from in situ observations and from kinematics should be identical for all $\bar{\sigma}$, provides a strong constraint on the galactic potential outside the solar orbit.

7. The evolution of metal abundance distribution with time

Previous gradient determinations indicate a gradient steepening for the very-young-disc population (see Mayor 1976; Grenon 1977). The present investigation shows that, except for very old disc stars for which the coarse method applied here is not fully valid, the gradient has not changed significantly during the history of the galactic disc, nor the mean metal abundance at given $\bar{\sigma}$.

The reasons for the discrepancy with previous results are multiple. When gradients are deduced from kinematics, the gradient flattening observed for old disc stars results from population mixing in the case of small $\bar{\sigma}$ (cf. Section 5), and from an overestimation of apocentric distances of stars with $\bar{\sigma} > \bar{\sigma}_0$ when Eggen, Lynden-Bell & Sandage (1962) model is adopted.

When samples of F-type stars are considered, an important selection bias against old solar abundance to SMR stars is made. It is clear from Fig. 9 that a selection of stars with spectral type earlier than G0 retains old stars near the turnoff only if their $[M/H]$ ratio is less than $-0.30$. In the case of SMR stars the spectral type at the turn-off is as late as G7 IV corresponding to a hydrogen-line type G2. The sample of F stars has, as a consequence, an apparent flattening of the gradient for old stars and an excessive dependance of $[M/H]$ on time at $\bar{\sigma}_0$.

An unbiased sample of stars should contain all subgiants, down to the spectral type K2 IV in order to include the old, evolved, metal-rich and SMR stars. In the case of dwarfs it should be defined by a limiting absolute magnitude, preferably $M > 5.5$, and not by a limiting colour index value.

Samples of field G and K giants are generally free of bias against metal-rich stars. Nevertheless, an age effect was found by Mayor (1976) working on the Hansen-Kjaergaard (1971) sample of K giants. When distances to the giants are deduced from spectroscopic luminosity estimators, a spurious age effect on the gradient may be
Galactic metal abundance gradient

Figure 9. The HR diagram of old NLTT and Gliese stars with $f$ parameter from 0.30 to 0.50. Note the abundance effect on the colour and spectral type at the turnoff. Symbols for $[M/H]$ intervals: □: ≤ −.50; △: −.49, −.30; ○: −.29, −.15; ●: −.14, +.14; +: +.15, +.29; ▲: ≥ +.30.

expected. Because of the spread of masses at given $T_{\text{eff}}$ and luminosity, the relations between a gravity parameter and the absolute magnitude are strictly valid only for a given stellar generation (Grenon 1979). If these relations are true for intermediate age stars, distances and space velocities of young massive stars are underestimated whereas those of old giants are overestimated. The amplitude of this effect is as follows: if a true gradient of $-0.10$ kpc$^{-1}$ is observed from $1.3\ M_\odot$ intermediate age stars, the Hyades generation giants lead to $-0.13$ kpc$^{-1}$ and the oldest giants to $-0.08$ kpc$^{-1}$ when galactocentric distances are deduced from space velocities.

Local irregularities of the stellar distribution may also affect the gradient determination. The presence in the solar vicinity of the Hyades cluster and associated group, with an $[M/H]$ higher than the mean for their mean $m$, produces some steepening of the gradient deduced from young stars with eccentricities less than 0.15.

The preceding considerations appear sufficient to explain why the gradient has been found to increase with time in previous investigations. Considering the similarity of the large-scale gradients found from young, massive stars, the open clusters, the interstellar matter, and the old disc stars we may conclude that the gradient did not change significantly in the disc during the last 8 to 10 billion years.
8. A global picture of the abundance distribution

Very few determinations of metal abundances are available for objects located near the galactic centre, i.e. for \( \sigma < 5 \) kpc. A very important set of observations were produced by Withford & Rich (1983) who have observed K giants in Baade's window. The abundance distribution of these inner bulge stars show a bulk of metal-rich stars and about one-third of stars with halo metallicities. The mean \([M/H]\) of metal-rich stars is \(+0.44 \pm 0.08\) or up to \(+0.60\) if a less conservative colour excess is adopted.

If we assume that this subpopulation has an age similar to that of SMR stars seen in the solar neighbourhood, i.e. about \(9 \times 10^9\) yr (Grenon 1984), and that it represents the inner extension of the old thick disc, it is possible to produce a global picture of the \([M/H]\) distribution in the old disc. The age of SMRs appears quite similar to that of the disc itself at \(\sigma_0\). For 9-billion-year-old stars, Twarog (1980) gives a mean \([M/H]\) = \(-0.30\) in the solar vicinity, irrespective of the stellar birthplaces. The old disc NLTT and Gliese stars with \(f\) between 0.30 and 0.70 show a higher metallicity at \(\sigma_0\) of about \(-0.15\) dex. Considering the high velocity dispersion observed near the galactic centre and the associated mixing of orbits, we may expect a flat distribution of \([M/H]\) at the centre. Adopting a quadratic law for the relation \([M/H]\) versus \(\sigma\) we have, for the old disc, gradients equal to \(-0.09\) kpc\(^{-1}\) for \(\sigma\) from 4 to 8 kpc, and \(-0.12\) kpc\(^{-1}\) from 8 to 12 kpc.

The young disc objects, \textsc{H} II regions and Cepheids seem to indicate a steepening of the gradient for \(\sigma < 7\) kpc. If real, this abundance increase might result from the intense stellar formation observed in the inner regions and from the gas inflow. In particular, in the so-called 3 kpc arm the present metallicity might well exceed that achieved in the central regions at the end of the bulge formation. In the outer regions the young-disc metal-abundance distribution has a shape very similar to that of old disc stars, with a mean abundance at solar galactocentric distance equal to \(-0.05\) dex.

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Galactic metal abundance gradient

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On a Possible Metallicity Gradient in SMR Stars

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Abstract. The possibility of existence of a metallicity gradient in super-metal-rich (SMR) stars is discussed. It is concluded that the SMR phenomenon was more active in the past than it is now.

Key words: stars, super-metal-rich—Galaxy, metallicity gradient—Galaxy, chemical evolution

1. Introduction

The enrichment in heavy elements has begun in the universe immediately after its birth and still continues. It is widely accepted that all elements as heavy as— or heavier than—carbon have been formed by nucleosynthesis in stellar interiors or during supernova explosions. At the present time the problem is to find out how the different star–interstellar-matter systems have been enriched in heavy nuclei during the phases of their evolution. From observations we know that the metal enrichment has not been uniform, neither in time, nor in location, in our own Galaxy. We know also that this metal enrichment is tightly bound to the nature of the nucleosynthesis which has acted in supernova explosions and, in much less efficient way, in the centre of red giants. One of the things we still poorly know, is the value of the upper limit of metal enrichment in stars: is it possible to find stars having metal abundances two, three or more times higher than that of the Sun?

Because this meeting is dedicated to low-mass stars, and because my paper is a very short one, I shall speak only of metal-rich solar type subgiants and dwarfs, leaving for another occasion the discussion on super-metal-rich (SMR) G and K giants. The convective zone of the slightly evolved or unevolved solar-type stars is sufficiently developed to prevent diffusion effects of chemical elements, and to avoid the Am-Ap phenomenon. We therefore can assume that in these stars the chemical composition of the atmosphere does reflect the initial chemical composition of the object.

2. Metal-rich G and K stars

Spinrad & Taylor (1969) called a star super-metal-rich if its overall metal to hydrogen ratio \([M/H]\), was higher than that of the Hyades:

\[
[M/H]_{\text{SMR}} > [M/H]_{\text{Hyades}}.
\]

This statement came back in my mind while finishing with Roger Cayrel and Bruce Campbell a spectral analysis based on high signal/noise C.F.H. Reticon spectra (Cayrel
et al. 1985). We obtained accurate abundances for metals (principally iron) in twelve Hyades solar-type dwarfs. The resulting iron abundances are very near solar value for two dwarfs (probably due to a high level of their chromospherical activity); for the remaining 10 stars the mean abundance is:

$$\left[ {\text{Fe/H}} \right]_{\text{Hyades}} = +0.12 \pm 0.03 \text{ dex}.$$ 

We choose the above value for the Fe abundance of the Hyades in selecting SMR candidates in the [Fe/H] Catalogue (Cayrel de Strobel et al. 1985). We surveyed the
Table 1. SMR/F, G and K dwarfs and subgiants.

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D: doubtful.

Catalogue in order to find stars having

\[ [\text{Fe/H}] \geq +0.12 \text{ dex} \]

We used then Spinrad & Taylor definition of SMR's as:

\[ [\text{Fe/H}]_{\text{SMR}} \geq +0.12 \text{ dex}. \]

We found that in the Catalogue exist

30 F, G and K dwarfs and subgiants,

and

60 G and K bright yellow giants,

satisfying the above condition.
These 90 stars represent 17 per cent of all the 539 stars contained in the $[\text{Fe/H}]$ Catalogue (edition January 1985).

As already said, today we shall speak only of 30 dwarf and subgiant SMR candidates. Table 1 gives relevant data for these objects: HD number, $B - V$, space velocity components: $U, V, W$, log $T_{\text{eff}}$, $M_{\text{bol}}$, $[\text{Fe/H}]$. The last two columns of this table contain two age estimations for the programme stars, one with the help of a metal-rich isochrone grid ($Z=0.034$) and one with a metal-normal isochrone grid. The metal-normal grid is from VandenBerg (1983), the metal-rich comes from an extrapolation of VandenBerg's grids.

The sample of dwarfs and subgiants contained in Table 1 is by no means a significative SMR star sample in our solar neighbourhood. Certainly many more SMR low-mass M dwarfs do exist. But detailed spectral analyses of such objects are very difficult and abundance results very doubtful. For instance, the only star in Table 1 that is metal-rich by a factor 4, with respect to the Sun, is the M1 dwarf HD 36395 analyzed by Mould (1978). Besides, only 17 per cent of the sample of 30 stars are 'super-metal-rich' by more than a factor of 2 and less than by a factor of 2.6 with the exception of Mould's star. The other stars are metal-rich by a factor of 2 down to 1.3 with respect to the Sun. It is also interesting to note that the 30 stars have rather high space-velocity parameters, showing that probably all belong to the old disc population.

With the help of the last two columns of Table 1 we tried to attribute a 'turn-off' age to the slightly evolved stars. The ages for the stars contained in the last column are spurious because they have not been obtained with the grid of isochrones computed with the appropriate $Z$. Fig. 1 reproduces the metal-enhanced grid and the positions in
Metallicity gradient in SMR stars

it of 29 SMR dwarfs and subgiants of which we have determined the bolometric magnitudes and effective temperatures.

The ages contained in the penultimate column have been used in constructing a [Fe/H] versus 'age' diagram. This diagram is shown in Fig. 2. Two different relations are displayed on it; the upper one refers to SMR stars, whereas the lower one comes from Twarog (1980) and is the general disc-star relation.

3. Conclusion

In conclusion we can say, that, there is an indication that the SMR phenomenon was more active in the past than it is now. Following Twarog (1980) we see that, in 10 Gyr the [Fe/H] abundance of disc stars has increased by approximately +0.4 dex, whereas the [Fe/H] abundance of SMR disc stars has diminished by 'very' approximately −0.1 dex. However, all along these last 10 Gyr, the SMR phenomenon did exist, but slightly damped.

A possible, but not unique, interpretation of this is that the interstellar medium in our Galaxy became progressively more chemically uniform with time.

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Chemical Evolution of Galaxies and Abundances in Low-Mass Stars

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Abstract. The chemical evolution of galaxies is discussed with reference to elemental abundances in low- and intermediate-mass stars.

Key words: galaxies, chemical evolution—stars, low- and intermediate-mass

1. Introduction

Since they are very numerous and they have a long life-time, low-mass stars play a crucial role in the evolution of galaxies. They can be used to determine the metallicity at the beginning of galactic evolution. Moreover, when one compares their abundance ratios with those observed in other sites they lead to a better understanding of the formation and the evolution of many nuclear species. After a very brief presentation of the main parameters which govern the evolution of galaxies like the rate of star formation, the stellar initial mass function and the nuclear yields, I will provide a list of the nuclear species which should be observed in low-mass stars in order to progress in the analysis of such evolutions.

2. The main parameters governing the galactic evolution

2.1 The Initial Stellar Mass Function

Salpeter (1955) has been the first to propose a simple relation between the relative number of stars $\phi(m)dm$ with respect to their mass $m$ at their birth.

$$\phi(m)dm \sim \int_{m_{\min}}^{m_{\max}} m^{-x} dm$$

(1)

where the exponent $x$ depends on $m$ such that $x(m) \sim 0.6$ for $m < 1.8 M_\odot$ and $\sim 2$ for $m > 1.8 M_\odot$ (see e.g. Miller & Scalo 1979; Scalo 1985 and Zinnecker 1986 for a more thorough presentation); $m_{\min}$ and $m_{\max}$ represent respectively the lower and upper limits of the stellar masses represented by this distribution. These two quantities may not be constant everywhere. For instance Güsten & Mezger (1983) have proposed a model for the chemical evolution of our Galaxy for which $m_{\min} = 0.1 M_\odot$ for the stars formed out of the spiral arms and $m_{\min} = 2 M_\odot$ for the stars formed inside them: this assumption has been made in order to account for the metallicity gradient with respect to the galactocentric distance. More recently Larson (1985) has built up a bimodal star-formation model fairly similar to the one of Güsten & Mezger (1983) but with no
reference to the galactic arms. Concerning \( m_{\text{max}} \), one may argue that \( m_{\text{max}} \sim 1/Z^\beta \) with \( \beta \sim 1 \) since the largest giant H II region complexes have been observed by Viallefond and collaborators in the external regions of the galactic disc of M101 where the metallicity should be the weakest.

2.2 The Rates of Star Formation

The classical Schmidt law \( dS/dt \sim \mu^\alpha \) such as \( 1 < \alpha < 2 \) where \( \mu \) and \( S \) are respectively the gas and the stellar density is most often used to parametrize the rate of star formation. The Schmidt law has been found to be a valid representation of the rate of star formation in the high-mass range by Guibert, Lequeux & Viallefond (1978) who deduced \( \alpha = 2 \) from the many tracers of high-mass stars.

It is very difficult to determine directly the rate of formation of low-mass stars. In a still unpublished work, G. Malinie, J. Audouze & M. Dennefeld (see a quotation of this work in Audouze, 1983) are attempting to use the planetary nebulae and the observations of their metallicity to deduce the rate of formation of low-mass stars. From their analysis they would conclude that \( S(t) \sim e^{-t/\tau} \) with \( \tau \sim 4 \pm 1 \times 10^9 \) years.

Audouze, Chiosi & Woosley (1986) are also investigating the possibility of a constant rate of star formation in the beginning of the galaxy evolution.

\[
S(t) = S_0
\]
for \( t < t_c \) and then \( dS/dt \sim \mu^\alpha \) for \( t \geq t_c \).

To summarize the remarks on the rate of star formation one should recall that this parameter is not always a continuous function: Bursts of star formation occur often in the course of evolution of a galaxy (see e.g. Larson & Tinsley 1978). Moreover, the rate of star formation can be stochastic according to Gerola & Seiden (1982, see also White & Audouze 1983).

2.3 The Yields

The yields concern the relative production of a given nuclear species by a distribution of stars. They are indeed related to the different nucleosynthetic contributions of the stars with respect to their mass (see e.g. the reviews of Audouze & Tinsley 1976, Tinsley 1980; Audouze 1983). The yields \( y_i \) concerning a species \( i \) can be written as:

\[
y_i = \sum_{i \neq j} X_j \int_{m_{\text{min}}}^{m_{\text{max}}} Q_{ij}(m) \phi(m) \, dm
\]

\[
1 - \sum_{i \neq j} X_j \int_{m_{\text{min}}}^{m_{\text{max}}} Q_{ij}(m) \phi(m) \, dm
\]  \hspace{1cm} (2)

In this relation \( Q_{ij} \) are the mass fraction of the nucleus \( j \) transformed into \( i \) in a star of mass \( m \); and \( X_j \) are the mass fractions of the element \( j \), \( \phi(m) \) is the initial mass function (IMF). The yield \( y_i \) of a stellar generation is defined as the mass of newly synthesized species \( Z_i \) per fraction of matter that is locked-up in long-living stars and remnants. The yields are also related to the constraints coming from the nucleosynthesis and stellar evolution. Audouze & Tinsley (1976), Gusten & Mezger (1983) and Gusten (1986) give a
list of yields of nucleosynthesis processes. It should be stressed at this point that spectroscopic studies of low-mass stars should provide valuable information regarding the determination of some of these yields.

3. A very quick tour in the nucleosynthetic ‘zoo’

Recent general accounts of the progress made in nuclear astrophysics are given in Barnes, Clayton & Schramm (1982), Audouze & Mathieu (1986), and Audouze, Chiosi & Woosley (1986). One can distinguish roughly four different nucleosynthetic sites:

1. Primordial nucleosynthesis is responsible for the formation of $^2$D, $^3$He, $^4$He, $^7$Li.
2. The interaction between the galactic cosmic rays and the interstellar medium explains the synthesis of $^6$Li, $^9$Be, $^{10}$B and $^{11}$B.
3. The low-mass stars $m < 5 M_\odot$ should be able to transform some of the $^{12}$C and $^{16}$O nuclei into species like $^{13}$C, $^{14}$N, $^{17}$O. They synthesize also the s-process elements. Moreover, $^{56}$Fe seems to be produced by stars less massive than those which form $^{16}$O. Planetary nebulae, novae and possibly Type I supernovae which can have an active nucleosynthetic role should come from low-mass star progenitors.
4. The high-mass stars are especially responsible for the formation of $^{16}$O and related elements between Ne and Ca. They terminate their evolution as Type II supernovae or/and Wolf-Rayet stars.

4. Relations describing the evolution of abundances and gas density during the galactic evolution

These relations are fairly classical and are described in more details in Vigroux, Audouze & Lequeux (1976) and Tinsley (1980). The evolution of the gas density and the abundances of an element $i$ are given by:

$$\frac{d\mu}{dt} = -\mu v + \int_{m_{\text{inf}}}^{m_{\text{sup}}} E(m)Q(t - \tau_m)vdmd\tau_m$$

where $v$ is the rate of astration, $E(m)$ the fraction of gas returned at the end of the stellar evolution, $\tau_m$ the lifetime of a star of mass $m$ such that $\tau_m = 10^{10}/m^8 + 10^6$ yr (one sees here the crucial role of low-mass stars which have a long lifetime such that $\tau_m$ cannot be neglected in the calculations), and $\delta_z$ is a term describing the possible accretion of gas in the considered zone

$$\frac{d(Z_i\mu)}{dt} = -\mu Z_i v + \int_{m_{\text{inf}}}^{m_{\text{sup}}} p_{Z_i} \phi(t - \tau_m)vdmd\tau_m$$

where $Z_i$ is the mass fraction of the element $i$ in the interstellar medium, $p_{Z_i}$ the fraction of this element produced in the stars and $\delta_{Z_i}$ the mass fraction of this element contained in the accreted gas. The study of low-mass stars is not only important because their $\tau_m$ is large but also because the determination of the different $p_{Z_i}$ depends critically on the abundance determination which concern them.

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5. A list of evolutionary problems related to low-mass stars

This list is of course far from complete. The reader is advised to exercise his/her own wisdom on this topic. One could divide the type of problems in which low-mass stars play a role in two classes—those concerning the elemental abundances and hopefully those concerning the isotopic ratios.

5.1 Elemental Abundances

In the sequel of the joint discussion, interesting remarks have been made by Kraft and other colleagues. I will therefore comment only on two points:

1. The concept of primary and secondary elements which has been introduced e.g. by Audouze & Tinsley (1976), might be a bit misleading. Let me recall that primary elements are defined as those which can be produced directly in any star while secondary elements are only formed from a first generation of primary elements. This classification should be replaced by that in which one separates the elements produced in high-mass stars which behave like primary elements and those which are produced in low-mass stars which behave like secondary elements.

2. Recently Matteucci (1986) studied the N problem and concluded that N is both a primary and secondary nucleosynthesis product; the primary N originated from high and intermediate stars, whereas the secondary nitrogen is from lower-mass stars. A consistent explanation for the origin of N is yet to be found. A similar problem exists in the case of s-process elements and isotopes (see Spite & Spite 1985; Iben 1985) whose synthesis in intermediate-mass stars or low-mass stars is not yet well-understood.

5.2 Isotopic Ratios

Isotopic measurements are especially important in this context because they provide valuable information on the relative contributions and properties of the different nucleosynthetic sites defined above. The synthesis of $^{13}$C, $^{15}$N and $^{17}$O are extremely different from those of $^{12}$C, $^{14}$N and $^{16}$O. Tomkin, Luck & Lambert (1976) find $10 < ^{12}$C/$^{13}$C < 35 in red giants, much smaller than the terrestrial value. Recently, Sneden & Pilachowski (1986) and Sneden, Pilachowski & VandenBerg (1986) determined carbon isotope ratios in old galactic cluster stars and field population II giant stars. Determination of the oxygen isotope ratios in low and intermediate-mass stars are valuable in understanding the stellar nucleosynthesis and galactic nuclear evolution. Recently, Harris, Lambert & Smith (1985) determined the oxygen isotope ratio in several MS and S stars. Wannier (1980, 1985) reviewed the CNO isotope ratios in red giants and the galactic evolution of the CNO nuclides. Schramm (1985) gave detailed review of the problems connected with the nucleosynthetic interpretations of isotopic anomalies. Clearly, we need more determinations of several isotopic ratios in low-mass and population II stars in order to be able to constrain the present models of stellar and galactic evolution.

Clayton (1985) presented a new analytic model of the chemical evolution of the
galaxy and suggested adopting this model as a reference standard for studies of chemical evolution.

6. Concluding remarks

Low-mass stars are the witnesses of the early phases of the galactic evolution. They should constrain the choice of the parameters governing the chemical evolution of galaxies. But for that purpose progress should be made in the determination of more elemental abundances and especially isotopic ratios which constitute the best input data to deduce the relative yields which are used in the galactic evolution models and also in refining the current analyses of various nucleosynthetic mechanisms.

Binaries are also important in the galactic nucleosynthesis. Since more than half of all stars appear to be members of binary systems it is important to consider the effects of binary evolution on nucleosynthesis, and consequently on galactic chemical evolution.

Acknowledgements

These introductory remarks have been written only to please Giusa Cayrel which is perhaps a sufficient motivation by itself. I thank Marie-Christine Pelletan for her quick and efficient typing of these notes.

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Vol. 7, p. 489.
A New Interpretation of the Metallicity Histogram of Globular Clusters

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Abstract. A new interpretation is given to the low metallicity peak of the bimodal metallicity histogram of galactic globular clusters. It is proposed that these globular clusters are primordial, i.e., formed out of big-bang matter. Their nonvanishing metallicity is attributed to pollution by supermassive stars like R 136a. The first stellar generation is formed out of the 'dirty' primordial matter.

Key words: globular clusters, formation—globular clusters, metallicity

1. Introduction

It is widely assumed that stars have the same chemical composition as the interstellar medium out of which they are born. However, this statement may well be only partially true because, when a cluster of stars is formed, the chemical composition of the cloud progenitor of the cluster has no reason to escape some degree of heavy elements pollution due to the formation of O-stars evolving very fast into supernovae (SN) within the cloud. Usually this phenomenon is inconspicuous because if, for example, we assume that 20 per cent of the heavy elements produced by the SNs of a cluster have polluted the cloud, the ensuing increase in metallicity $\Delta Z$ for the cloud is of the order of:

$$\Delta Z = 0.2 \text{ yr}$$

where $y$ is the yield and $r$ the stellar formation efficiency (fraction of the gas turned into stars in the cloud).

Assuming a stellar formation efficiency, $r \approx 0.08$, (Cohen & Kuhi 1979), and a yield of 0.02 (Matteucci 1983) gives $\Delta Z \approx 0.0003$, quite small compared to the present value of $Z$ in the disc ($Z \approx 0.02$).

However if the initial chemical composition of the cloud is $Z = 0$ (primordial cloud) the resulting $Z$ is of the order of the metallicity of a globular cluster and the whole concept of population III is deeply shaken. In this paper we reconsider the metallicity histogram of the globular clusters according to the view that the clouds, progenitors of globular clusters, are primordial, as initially assumed by Peebles & Dicke (1968).

2. The bimodality of the metallicity histogram for galactic globular clusters

Zinn (1985) has convincingly shown that two stellar populations can be identified within the metallicity histogram of galactic globular clusters (Fig. 1).
Figure 1. Metallicity histogram of globular clusters according to Zinn (1985). The two metallicity peaks correspond to two subsets of clusters having very different spatial and kinematical properties.

The low metallicity peak ([Fe/H] = −1.6) in the histogram corresponds to a subset of globulars having a spheroidal distribution and virtually no rotation around the galactic centre. The high metallicity ([Fe/H] = −0.5) subset has a very substantial degree of flattening and a mean rotation of about 170 km s\(^{-1}\), only 25 per cent less than the rotation of the disc. We have plotted in Fig. 2 the metallicities of globular clusters as a function of their absolute magnitude (no correlation) and of their distance to the galactic plane. It is clear that the subset within ±2 kpc from the plane is more metal rich than the subset with distances to the galactic plane between 2 and 4 kpc, and that clusters more distant than 4 kpc from the galactic plane are still less metal rich. If we redraw Zinn’s histogram using a linear scale instead of a logarithmic scale (Fig. 3) we see that the metal-poor clusters are highly concentrated near Z ≃0, whereas the intermediate metallicity clusters have a fairly flat distribution.

We are proposing here that the flattened system reflects the progressive formation of clusters in a protogalaxy in which metallicity increases as the protogalaxy becomes flatter, as evidenced by Fig. 2. It is then quite understandable that the globular clusters of the flat subset have a metallicity comparable to the initial mean metallicity of the disc (Z ≃0.25 Z\(_\odot\), according to Twarog 1980). This is the ‘classical’ view of an age-metallicity relationship as suggested by Eggen, Lynden-Bell & Sandage (1962). The absence of younger galactic globular clusters is then explained by the shear of the galactic rotation, preventing the gravitational instability of large structures. We depart
Metallicity histogram of globular clusters

Figure 2. The metallicity of globular clusters as depending upon their visual magnitude and their spatial distribution. Symbols are as follows: ●: globulars within 2 kpc from the galactic plane; ○: globulars with distances to the galactic plane between 2 and 4 kpc; □: globulars with distances to the galactic plane larger than 4 kpc.

Figure 3. Metallicity histogram of globular clusters according to Zinn (1985). The abscissa is now linear in $Z$.

from the classical view, however, in claiming that the low-metallicity, spheroidal system is primordial, i.e., formed out of big-bang matter as initially proposed by Peebles & Dicke (1968).

The only objection to this concept is that the globular cluster stars should be
population III stars \textit{i.e.} stars with $Z=0$. But as we said in the introduction, the view that a primordial cloud produces stars without any degree of self pollution is rather questionable. In other words the idea that the signature of the first stellar generation is $Z=0$, does not take into account the ecology of star formation. As the only stars still visible in globular clusters have masses below $0.9 \, M_\odot$, the crucial point is to know if stars of such masses have been (on the average) born before any supernova has contaminated the progenitor cloud, or not. We are actually considering this point in the next paragraph. For the time being we assume that each globular cluster in the spheroidal system has generated its own metals, and that each globular of the spheroidal system is chemically independent of the others. We compare in Fig. 4 the close-up of the lower metallicity group of the histogram with (i) a theoretical curve obtained by Searle (1977), (ii) a simple log-normal law fitted to the observed distribution. The bin with the lower metallicity ($Z=0$ to 0.005 $Z_\odot$) has a crucial importance. If this bin is actually empty, or nearly empty (the only globular cluster in this bin is NGC 5053 and has a poorly determined metallicity) the log-normal law is a better fit than Searle's law, which is based on a progressive enrichment model, but with some stochastic component in it. The purely stochastic log-normal law is quite an acceptable law for a self-pollution model as ours: the number and the masses of the polluting SNs, the dilution factor of the pollution in the primordial gas, \textit{etc.} are stochastic in nature, and it is known that when a variable is expressed as the product (or ratio) of several stochastic variables, this variable tends to have a log-normal distribution. Anticipating the results from the next section we even connect the existence of this first empty bin to a basic process in star formation: if the first bin is actually empty it means that no low-mass stars can form unless an SN has already exploded in the medium.

One must of course question whether the width of the log-normal law is determined by the observational errors in metallicity. The error is actually merely gaussian in
[Fe/H], leading to a log-normal law by itself. However, the width due to the observational error is $\delta \log Z \simeq 0.15$ according to Zinn & West (1984), significantly smaller than the combined width of the intrinsic distribution and of observational errors ($\delta \log Z \simeq 0.3$ in Fig. 4).

To summarize this section, we believe that the low metallicity subset of the galactic globular clusters, i.e., the spheroidal subset, is primordial, with a metallicity histogram resulting from the stochastic self-pollution of the initial zero-metal progenitor cloud having enriched the low-mass stars born a little later in the cloud which are being observed today.

3. The gravitational collapse of a primordial cloud

The cloud progenitors of globular clusters cannot have a mass smaller than the mass of the present-day clusters and, unless star formation was extraordinarily efficient, may very well have been 10 to 50 times more massive. As the typical mass of a present-day globular cluster is $10^5 M_\odot$ the typical mass of a progenitor must have been in the $10^6$–$10^7 M_\odot$ range. When such a cloud becomes gravitationally unstable it begins to collapse, each layer taking an inward motion towards the centre of the cloud, over timescales corresponding to a free fall under the gravitational pull of all the matter inside this particular layer. Detailed computations (Larson 1978) show that whereas the free-fall model is a good approximation in the central parts of the cloud, a pressure gradient counteracts the gravitational pull in the rest of the cloud, which evolves into a dense core reaching a very high density in a free-fall time $(3\pi/32 G\rho)^{1/2}$ (where $G$ is the gravitational constant and $\rho$ the density) surrounded by an envelope which evolves slower. In the absence of Eddington instability (role of the radiative force balancing the gravity at the surface of very luminous objects) and the occurrence of fragmentation, the core of a collapsing cloud would likely form a very massive object, the luminosity of which would stop the further accretion of mass from the envelope. We claim that such a (hypothetical) very massive object must fragment at least to the level of the most massive existing stars, i.e. to the most massive O-stars. Carr, Bond & Arnett (1981), and El Eid, Fricke & Ober (1981) discuss the evolution of, and nucleosynthesis in, such primordial, very massive stars. We propose that the bulk of the low-mass stars is formed in the gigantic shock between the still infalling envelope and the expanding medium formed by the stellar winds and by supernova shells of the fast evolving central massive stars. The fragmentation to smaller masses is then made much easier by the Rayleigh-Taylor instability occurring at the boundary between the expanding central ‘bubble’ and the cooler infalling medium, by the shock-enhanced density and by the presence of a few heavy elements supplying additional cooling mechanisms. Although this scenario is qualitatively attractive and would explain the first empty bin in the globular cluster histograms, we must admit that the theory of star formation has not yet reached a state that would permit detailed predictions. We believe that the strongest argument in support of the early occurrence of O-stars in the cloud is drawn from observation and will be developed in the next section.

The ‘secondary’ SNs, formed with the low-mass stars, inject so much energy in the cloud that after its short life as an H II region the cloud is disrupted.

Only a minority of stars have velocities low enough to remain bound to the central cluster, after most of the initial mass has been expelled. So we expect that the main
product of the process is not the cluster but an association whose expansion velocity is
drawn from the initial stellar winds and SN explosions at the centre (first star-
formation region). The stars of these former associations could be the present field
population II.

The complete suggested sequence of events is therefore: gravitational collapse→
cloud with high density core→cloud with a central cluster of O-stars→association with
expanding gas and star system→globular cluster (still existing or dissolved in the field)
+ field population II + gas collected by the galactic disc.

4. The cores of 30 Doradus and NGC 3603

We have assumed that the first stellar formation in a collapsing cloud was (i) at the
centre, and (ii) rich in massive stars capable of taking control of further evolution of
the cloud. If this is true for primordial clouds it should also be true of present-day more
metal-rich giant clouds. The nearest giant H II region with a mass \( \approx 10^6 M_\odot \) is
30 Doradus in the large Magellanic cloud. It is precisely at the centre of 30 Doradus
that a supermassive object has been suspected for many years. This central object
R 136a has a luminosity of \( 10^7 L_\odot \) and is responsible for the ionization of a large part of
30 Doradus. Recent observations (Weigelt 1981; Walker & O'Donoghue 1984)
however have shown that the object is multiple and has a composite spectrum of O and
Wolf-Rayet stars. It is now believed that R 136a is a compact cluster (diameter < 0.3 pc)
of over 20 massive early-type stars. The nearer, but smaller, H II region NGC 3603 has
also a still more compact group of O stars at its centre. We think that this observational
fact is the strongest argument in favor of our assumption that something similar has
happened in population II star-formation regions.

5. Consequences on the chemical composition of population II and the chemical
evolution of the galaxy

An immediate consequence of our proposed scenario is that the first low-mass stellar
generation has been selectively polluted by ejecta of SNs due to very massive stars.
Current observation of H II regions seem to show that the whole burst of star formation
does not last longer than \( \sim 5 \times 10^6 \) years.

The more prominent characteristic of heavy element production in massive SNs is
the fact that they produce more oxygen in proportion of the metals as compared to the
ratio in the Sun. Although the results for oxygen/iron ratio in globular cluster giants are
somewhat scattered, it is a well-known observational fact that population II dwarfs
show a O/Fe ratio about four times the solar value (Sneden 1985). An analysis of Arnett
(1978) yields shows that such a ratio is expected from SN having progenitor O-stars of
mass \( \geq 50 M_\odot \). This is in perfect agreement with our scenario, the most massive stars
being at the same time the fastest and the most energetic, able to take control of the fate
of the collapsing cloud.

The heavy elements caught in globular cluster stars are, however, a very tiny fraction
of the total production of heavy elements during the first stellar generation of the
Galaxy.
Metallicity histogram of globular clusters

The total amount of population II is likely to be about 10 per cent of the mass of the Galaxy. If the yield for this stellar generation has been $\approx 0.02$ (Matteucci 1983), then the value of $Z$ at the end of the first stellar generation (population II = population III in our view) was $0.1 \times 0.02 = 0.002 = 0.1 Z_\odot$, a value corresponding fairly well to the transition value between actual population II and early disc value. This may also explain the so-called G-dwarf problem (Pagel & Pachett 1975) as the metallicity of the disc having been already brought to a high value by the first stellar generation.

6. Conclusion

We have developed arguments in favour of the concept that a first stellar generation in the Galaxy did originate from 'dirty' primordial matter and comprises of the old-known population II globular clusters, and field population II stars; a large fraction of the metallicity of the early disc is a product of this first stellar generation.

The fact that the first stellar generation is dirty is attributed to the early formation, at the centre of a collapsing massive cloud, of a compact cluster of O-stars like R 136a in 30 Doradus. The heavy elements produced by the supernovae of this central cluster are thought to be the main pollutant of the first stellar generation. This first population is oxygen-rich.

References

Concluding Remarks

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An obvious impression from this quite interesting session is that the study of abundances of low-mass stars is very essential for several reasons. In particular, the considerable ages of these stars, the possibilities to determine their ages, and the absence for almost all elements of effects of interior nuclear burning on the atmospheric abundances, at least for the dwarfs, make these studies vital in the investigation of the chemical history of the Galaxy and, for He and Li, of the universe as a whole. However, the results and problems presented in this session also demonstrate the need for a high, or improved, accuracy in the abundance determinations. Fortunately, such improvements are within reach with methods already available or soon to come.

The following comments deal with the trends in relative abundances and the scatter around these trends.

Trends. The variations of the relative abundance ratios, as functions of heavy-element abundances, are competently reviewed by Bob Kraft and David Lambert. The situation is schematically summarized in Lambert’s Figs 12 and 13, where also our imperfect knowledge, in particular for stars with [Fe/H] < −2, is indicated by broken lines.

It seems reasonable to attempt interpretations of these tendencies in terms of nucleosynthesis and galactic evolution. However, several circumstances indicate that caution is well motivated:

Late-type stars with lower overall metal abundance deviate in several important respects from their more metal-rich counterparts. e.g., the metal-poor atmospheres are more transparent, which should make the spectral effects of the hydrogen convection zone more important. Also, the higher transparency in the ultraviolet (due to the weaker spectral-line blocking) increases the possibilities for non-local ionization and excitation.

The risks that these stellar departures from standard plane-parallel local-mixing-length LTE model atmospheres could induce some of the abundance tendencies traced must be remembered and systematically investigated by more realistic model calculations. Such calculations are, at least partially, within reach today (cf., Nordlund 1985; Scharmer & Carlsson 1985). Also, semiempirical modelling should be pursued further (cf. Magain 1985). As long as this programme has not been completed one should seek ‘independent’ empirical confirmation of the abundance tendencies traced (e.g., from other spectral lines, other ions or molecules, other types of stars). Inconsistencies showing up at such checks are interesting as such and should be analysed carefully—probable or possible examples are the disparate Al and Ni abundances, discussed by Lambert and (in the case of Ni) by Bessell & Norris. Other examples of such inconsistencies were reviewed by Gustafsson (1983) who also gave a number of general comments on the determination of abundances for metal-poor stars.

Other abundance trends, e.g., with effective temperature, may also indicate that
something is wrong. Two examples were provided at this session—Kraft discussed the tendency for N/C to change rather drastically with $T_{\text{eff}}$, and Grenon mentioned that, at a given galactocentric distance, the cooler supergiants analysed by Luck appear more metal poor than the hotter ones. At least in the latter case one might suspect that the problem is related to the veiling effects of weak molecular bands, thus lowering the quasi-continuum with respect to the model spectra. This possibility, worrying all of us interested in abundances of cool stars, should be studied further.

Finally, however, one should note the reassuring result by Bessell & Norris that their remarkable very metal-poor star CD $-$ 38°245 shows normal population II relative abundances.

**Scatter.** For various astrophysical problems, the physical star-to-star scatter in an elemental abundance or in an abundance ratio, *e.g.* at a given stellar age, is of great interest. Since this scatter is often not much greater than the normal observational uncertainties an estimate of it requires high accuracy in the abundance analysis and methods for obtaining a realistic estimate of this accuracy.

The problem is clearly illustrated in the papers by Kraft, Lambert, Duncan & Hobbs, and Cayrel de Strobel. In the first two papers the quite important question is whether the considerable scatter in various abundance ratios such as $[\text{O/Fe}], [\alpha/\text{Fe}], [\text{Na/Fe}], [\text{Al/Fe}]$ for population II stars is real, or just reflecting the uncertainties in observations and analyses. Lambert suggests that most of it may be 'observational'—obviously more detailed and homogeneous studies are necessary to trace the true chemical inhomogeneities in the early halo gas. Such studies should, however, be feasible with current instrumentation.

Duncan & Hobbs suggest that there is a real scatter in the Li abundances for halo dwarfs at solar temperatures. This would then question the interpretation by Spite & Spite (1982) that these stars show a primordial Li abundance of cosmological significance. The interesting possibility certainly requires further study—however, one should also note the finding that the strength of the solar $\lambda 6708$ Li line is weak in plages, which may be interpreted as an overionization effect due to the enhanced non-radiative heating (Giampapa 1984). May be that the problem with the discrepant stars that show small chromospheric activity and still strong Li lines, discussed by Duncan & Hobbs, is related to this phenomenon.

Giusa Cayrel de Strobel has selected stars with $[\text{Fe/H}] > [\text{Fe/H}]_{\text{Hyades}}$ from the Cayrel et al. catalogue, estimated their ages, and obtained a very interesting diagram (her Fig. 2). She suggests that the SMR phenomenon was more active in the past than now, and that the interstellar medium in the disc may have become gradually more chemically homogeneous with time. One possibility, along the lines of Roger Cayrel's paper, might be that the SMR stars in general were formed in cloud complexes, considerably polluted by their supernovae before they were dissolved, while the general disc stars were produced in the more well-mixed and gradually enriched interstellar medium. However, these speculations are based on an inhomogeneous set of data, with a considerable and not well-known observational scatter. A more homogeneous and precise sample of data should be obtained to confirm and further illuminate Cayrel de Strobel's result. Note in this connection the bimodal metallicity distribution obtained by Grenon for his age group $0.3 \leq f \leq 0.5$ (his Fig. 6).

Grenon's study of the overall metallicity gradients in the Galaxy is very instructive. In particular, he demonstrates how vital a precise definition of an unbiased sample of
Concluding remarks

stars used for tracing an abundance gradient is, how serious the effects of mixing stars of different ages and different places of birth may be, etc. The importance of avoiding errors in calibrations of temperature and gravity dependences in [Fe/H] measures is also noteworthy. Independent attempts to verify Grenon's results, e.g. from studies based on photometric instead of dynamic age determinations, will be of great interest.

Final remarks. The comments made above have been mainly of methodological character. This should not be taken to imply that the astrophysical results presented in the session were less interesting. The comments by Audouze and Lambert on the unsatisfactory use of the notions 'primary' and 'secondary elements' and on the importance of determining isotopic ratios, the astrophysical implications of the trends discussed by Kraft and Lambert, the result that the nitrogen-rich population II dwarfs seem to be the result of binary evolution that was mentioned by Carney, Kraft and Spite & Spite, the finding by Grenon that the metallicity gradient in the Galactic disc does not seem to change appreciably with time and, not the least, Roger Cayrel's suggestive scenario of star formation and nucleosynthesis in proto-globular-clusters, which at least qualitatively seems to explain the absence of population III, the relatively high oxygen abundances of population II stars and the so-called G-dwarf problem; all these and several other points and results presented during the session made it very valuable, also for the result-oriented astrophysicist. I would like to add to the list the interesting contributions by Cathy Pilachowski which I, however, have no possibility to discuss further here. Thus, it is well motivated, indeed, to thank Giusa Cayrel de Strobel for having arranged the session.

References

Subject Index

Abundance gradient 123, 141
Abundance ratios
[Al/Fe] 97, 115, 120, 162
[Al/Mg] 103
[CN/Fe] 117
[C/Fe] 89, 117
[C/H] 91
[C+N+O/H] 115, 120
[Ca/Fe] 108
[CN/H] 124
[Eu/Fe] 117
[Fe/H] 83, 89, 93, 99, 103, 123, 142, 161
[Li/H] 81
[Mg/Fe] 103
[Mg/H] 112, 115
[N/C] 91, 119, 162
[N/Fe] 93, 117, 119, 123
[N/H] 93, 123, 128
[N/O] 119
[Na/Fe] 112, 120, 162
[Na/Mg] 103
[Ne/Fe] 110, 118
[O/H] 119
[O/Fe] 89, 101, 117, 158, 162
[Odd-even/x] 118
[Odd-even/Mg] 103
[Si/Ca] 120
[Si/O] 119
[Si/Fe] 103
[Si/Fe] 117
[Ti/Fe] 110, 118
α-nuclei 103
31 Aql 142
Baade's Window 138
Big bang model 81, 83, 153
Carbonaceous chondrites 86
C-burning 110, 120
CD 38° 245 90, 99 162
α Cen A, B 142
Cepheids 123
CN-strong stars 116
Cosmic rays 149
Curve of growth 86
Computer programmes
ATLAS6 84
MARCS 105
WIDTH6 86, 101
Disc stars 103, 123
30 Dor 158
Dwarfs 89, 93, 103, 141
Elements
Al 93, 103, 161
B 149
Ba 105, 117, 120
Be 149
C 89, 115, 125, 128, 129
Ca 103, 149
Cr 99
Eu 105, 116
Fe 83, 89
He 81, 129, 161
K 105
Li 81, 83, 93, 161
Mg 103
N 89, 93, 115, 125, 128, 150
Na 95, 103
Ne 149
Ni 99, 118, 161
O 89, 99, 115, 125, 128
Sc 104
Si 103
Sr 116
Ti 105, 118
V 105
Y 105
Galaxies
blue compact 81
Chemical evolution 147
Sc 130
Galaxy
Chemical evolution 94, 103, 141, 150, 161
G-dwarf problem 159, 163
Giants 99, 103, 123, 150
Globular clusters 92, 94, 116, 153
H II regions 123, 148, 158
Halo stars 83, 93, 103
H-burning 115
HD 1461 143
2796 101
10307 143
10780 143
19445 86, 110
25329 93
30562 143
30652 143
34411 143
36395 143
<table>
<thead>
<tr>
<th>Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>HD 74000 95</td>
</tr>
<tr>
<td>75732 143</td>
</tr>
<tr>
<td>86728 143</td>
</tr>
<tr>
<td>88230 143</td>
</tr>
<tr>
<td>97916 93</td>
</tr>
<tr>
<td>102634 143</td>
</tr>
<tr>
<td>102870 143</td>
</tr>
<tr>
<td>104304 143</td>
</tr>
<tr>
<td>107213 143</td>
</tr>
<tr>
<td>114710 143</td>
</tr>
<tr>
<td>120136 143</td>
</tr>
<tr>
<td>121370 143</td>
</tr>
<tr>
<td>122563 99</td>
</tr>
<tr>
<td>124570 143</td>
</tr>
<tr>
<td>128620 143</td>
</tr>
<tr>
<td>128621 143</td>
</tr>
<tr>
<td>134169 85</td>
</tr>
<tr>
<td>140283 100, 110, 112</td>
</tr>
<tr>
<td>145675 143</td>
</tr>
<tr>
<td>157881 143</td>
</tr>
<tr>
<td>160617 95</td>
</tr>
<tr>
<td>160691 143</td>
</tr>
<tr>
<td>161797 143</td>
</tr>
<tr>
<td>166913 143</td>
</tr>
<tr>
<td>182572 143</td>
</tr>
<tr>
<td>187691 143</td>
</tr>
<tr>
<td>187923 143</td>
</tr>
<tr>
<td>190248 143</td>
</tr>
<tr>
<td>190360 143</td>
</tr>
<tr>
<td>201891 86</td>
</tr>
<tr>
<td>217014 143</td>
</tr>
</tbody>
</table>

He-burning 125
High-mass stars 148
Hyades 86, 133, 137
ν Ind 114
Initial mass function 147
Intermediate-mass stars 119, 147
Interstellar medium 86, 128

<table>
<thead>
<tr>
<th>Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{17}$O 149</td>
</tr>
<tr>
<td>$^{18}$O 115, 120</td>
</tr>
<tr>
<td>$^{28}$Si, $^{29}$Si, $^{30}$Si 103</td>
</tr>
<tr>
<td>Isotopic ratios 90, 150, 163</td>
</tr>
<tr>
<td>$^{27}$Al/$^{24}$Mg 111</td>
</tr>
<tr>
<td>$^{12}$C/$^{13}$C 90, 150</td>
</tr>
<tr>
<td>$^{23}$Na/$^{24}$Mg 111</td>
</tr>
<tr>
<td>$[^{26}\text{Mg}/^{24}\text{Mg}]$ 114</td>
</tr>
<tr>
<td>$[^{28}\text{Mg}/^{24}\text{Mg}]$ 114</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lines and bands</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al I 112, 114</td>
</tr>
<tr>
<td>Ca I 110</td>
</tr>
<tr>
<td>Ca I λ 6717 85</td>
</tr>
<tr>
<td>Ca II K 131</td>
</tr>
<tr>
<td>CH 99, 112</td>
</tr>
<tr>
<td>CH (G band) λ4300 89</td>
</tr>
<tr>
<td>CH C-X band 100</td>
</tr>
<tr>
<td>CN λ3880 90</td>
</tr>
<tr>
<td>Cr II 99</td>
</tr>
<tr>
<td>Fe I, Fe II 105</td>
</tr>
<tr>
<td>Li I λ6707 84, 162</td>
</tr>
<tr>
<td>Mg Iβ 109,</td>
</tr>
<tr>
<td>MgH A-X 114</td>
</tr>
<tr>
<td>Mn II 90, 99</td>
</tr>
<tr>
<td>Na I D 114</td>
</tr>
<tr>
<td>NH λ3360 90, 99</td>
</tr>
<tr>
<td>Ni I λ3400 99</td>
</tr>
<tr>
<td>[O I] λ6300, λ6363 89, 99</td>
</tr>
<tr>
<td>O I λ7772–75 89, 99</td>
</tr>
<tr>
<td>OH λ3100 89, 99</td>
</tr>
<tr>
<td>OH (0,0) 101</td>
</tr>
<tr>
<td>OH (0,1) 101</td>
</tr>
<tr>
<td>Si II 110</td>
</tr>
<tr>
<td>Ti II 99</td>
</tr>
<tr>
<td>V II 99</td>
</tr>
</tbody>
</table>

| LMC 128, 158 |
| Low-mass stars 81, 147, 161 |
| Lunar samples 86 |
| M 31 128 |
| M 67 126 |
| M 101 148 |
| Metal-poor stars 99 |
| Meteorites 87 |
| Model atmospheres 84, 86, 95 |
| Neutrinos 81 |
| NGC 188 126 |
| NGC 3603 158 |
| NGC 5053 156 |
| Novae 149 |
| Nucleosynthetic yields 148, 153 |
| Odd-even nuclei 103 |
| Open clusters 86, 123, 150 |
| Plages 162 |
| Planetary nebulae 124, 148 |
| Pleiades 86 |
| Population II 81, 158, 162 |
## Index

<table>
<thead>
<tr>
<th>Population III</th>
<th>153</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary elements</td>
<td>118, 150</td>
</tr>
<tr>
<td>Primordial abundances</td>
<td>81, 83, 93, 149, 153, 162</td>
</tr>
<tr>
<td>R 136a</td>
<td>153, 158</td>
</tr>
<tr>
<td>r-process elements</td>
<td>116, 120</td>
</tr>
<tr>
<td>s-process elements</td>
<td>110, 116, 149</td>
</tr>
<tr>
<td>Secondary elements</td>
<td>118, 150</td>
</tr>
<tr>
<td>SMC</td>
<td>128</td>
</tr>
<tr>
<td>Space velocities</td>
<td>83</td>
</tr>
<tr>
<td>Star-formation rate</td>
<td>148</td>
</tr>
<tr>
<td>Stellar orbits</td>
<td>130</td>
</tr>
<tr>
<td>Stochastic star formation</td>
<td>148</td>
</tr>
<tr>
<td>Subdwarfs</td>
<td>83, 89</td>
</tr>
<tr>
<td>Subgiants</td>
<td>106</td>
</tr>
<tr>
<td>Supergiants</td>
<td>123, 162</td>
</tr>
<tr>
<td>Super-metal-rich stars</td>
<td>133, 141, 162</td>
</tr>
<tr>
<td>Supernitrogen stars</td>
<td>92</td>
</tr>
<tr>
<td>Supernova remnants</td>
<td>124, 130</td>
</tr>
<tr>
<td>Supernovae</td>
<td>149, 153</td>
</tr>
<tr>
<td>T Tauri stars</td>
<td>86</td>
</tr>
<tr>
<td>3-kpc arm</td>
<td>138</td>
</tr>
<tr>
<td>Wolf-Rayet stars</td>
<td>149, 158</td>
</tr>
</tbody>
</table>