

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 α -nuclei (Mg, Si, and Ca), and the odd-even nuclei (Na and Al, also ^{25}Mg and ^{26}Mg).

The α -nuclei are overabundant (relative to Fe) in the old disc and halo stars. Halo stars ($[\text{Fe}/\text{H}] < -1.2$) have $[\alpha/\text{Fe}] \sim 0.3$ with extreme halo ($[\text{Fe}/\text{H}] \lesssim -2.0$) stars showing possibly higher overabundances. The scatter in $[\alpha/\text{Fe}]$ at a given $[\text{Fe}/\text{H}]$ 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 $[\text{Fe}/\text{H}]$. Halo stars ($[\text{Fe}/\text{H}] < -1$) show $[\text{Na}/\text{Mg}] < 0$ and $[\text{Al}/\text{Mg}] < 0$, but the form of the mean relation and the scatter about the relation between $[\text{odd-even}/\text{Mg}]$ and $[\text{Fe}/\text{H}]$ 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 $[\text{Fe}/\text{H}]$.

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.*, ^{24}Mg , ^{28}Si) and odd-even nuclei (*e.g.*, ^{23}Na , ^{27}Al , ^{25}Mg) 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] \geq -0.9). Effective temperatures were taken from colours and the $H\beta$ 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_{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.*, $[\text{Fe}/\text{H}] < -1.0$ 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 coude 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_{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 $[\text{Fe}/\text{H}]$ values from about 20 Fe I lines is only 0.05 dex for a typical star—all values fall within ± 0.10 dex of the mean. The light elements available are Na, Mg, Al, Si, and Ca. Titanium which behaves much like an α -element was also included along with Ni, and the heavy elements Y and Ba.

4. Francois (1986, hereinafter F): High-resolution Reticon spectra from the CES at ESO and the coude 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_{eff} and $\log g$ —were taken from published analyses as provided by the 'Catalogue of $[\text{Fe}/\text{H}]$ Determinations' (Cayrel de Strobel *et al.* 1985). MARCS models with solar gf -values were adopted for the abundance analysis.

5. Gratton & Snenen (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.*, $[\text{Fe}/\text{H}] < -1$) and one quarter to the extreme halo (*i.e.*, $[\text{Fe}/\text{H}] < -2$). 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_{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 $[\text{Fe}/\text{H}]$) 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 α -Elements

The α -elements provided to varying levels of completeness by the five sources are Mg, Si, and Ca. In Fig. 1, I show $[\text{Si}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ for four of the samples; the fifth (LB) is the only sample to be based on photographic spectra. Each of the α -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 α -elements. Inspection of these two figures shows that the scatter at a fixed $[\text{Fe}/\text{H}]$ is reduced noticeably in Fig. 2 relative to Fig. 1.1 suggest that this reduction results from a partial cancellation of measurement errors when the mean $[\alpha/\text{Fe}]$ 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 $[\alpha/\text{Fe}]$ abundances versus $[\text{Fe}/\text{H}]$ 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 α -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, $[\alpha/\text{Fe}]$ is apparently constant. The mean value may be slightly positive; *i.e.*, the Sun is apparently slightly deficient in the α -elements. The scatter in $[\alpha/\text{Fe}]$ is small.

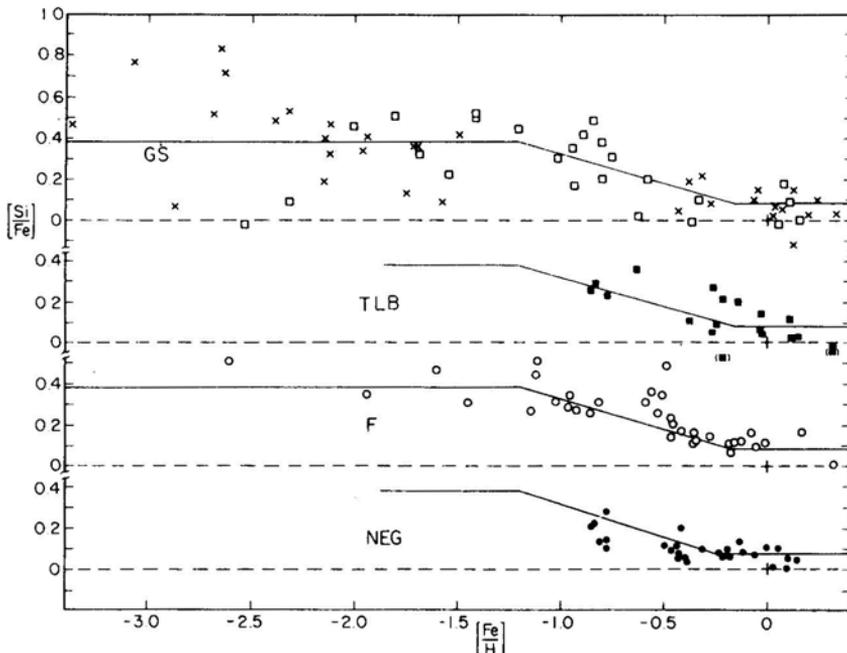


Figure 1. $[\text{Si}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ for the samples analysed by GS, TLB, F, and NEG. Giants ($\log g < 3.0$) in GS's sample are denoted by crosses, and dwarfs and subgiants ($\log g \geq 3.0$) by open squares. The points corresponding to the two K0 dwarfs in TLB's collection of dwarfs are placed in parentheses. The identical lines drawn through the data are approximate fits, not least-squares solutions.

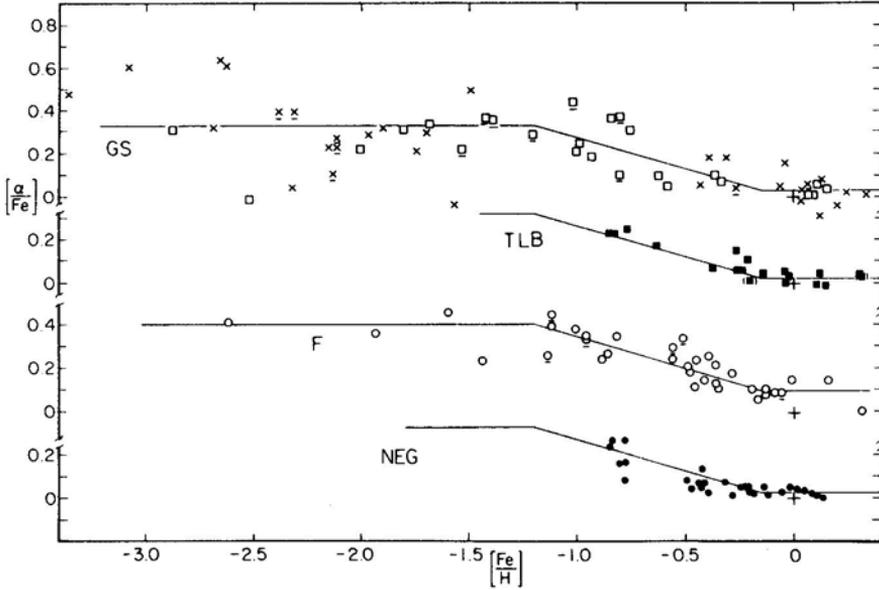


Figure 2. $[\alpha/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ for the samples analysed by GS, TLB, F, and NEG. See caption to Fig. 1 for comments on the symbols. The elements contributing to $[\alpha/\text{Fe}]$ are Mg, Si, and Ca for the GS, TLB, and NEG samples and Mg and Si for F's samples. For those stars where the abundance of one of the contributors to the mean $[\alpha/\text{Fe}]$ 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 $[\alpha/\text{Fe}]$.

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

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

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

$$[\alpha/\text{Fe}] = A_\alpha \quad \text{for } [\text{Fe}/\text{H}] \geq -0.15,$$

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

$$[\alpha/\text{Fe}] = A_\alpha + 0.30 \quad \text{for } [\text{Fe}/\text{H}] < -1.2.$$

The constant $A_\alpha = 0.05$ appears to fit most of the data; *i.e.*, the Sun appears to be slightly α -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_α 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_α and the intrinsic

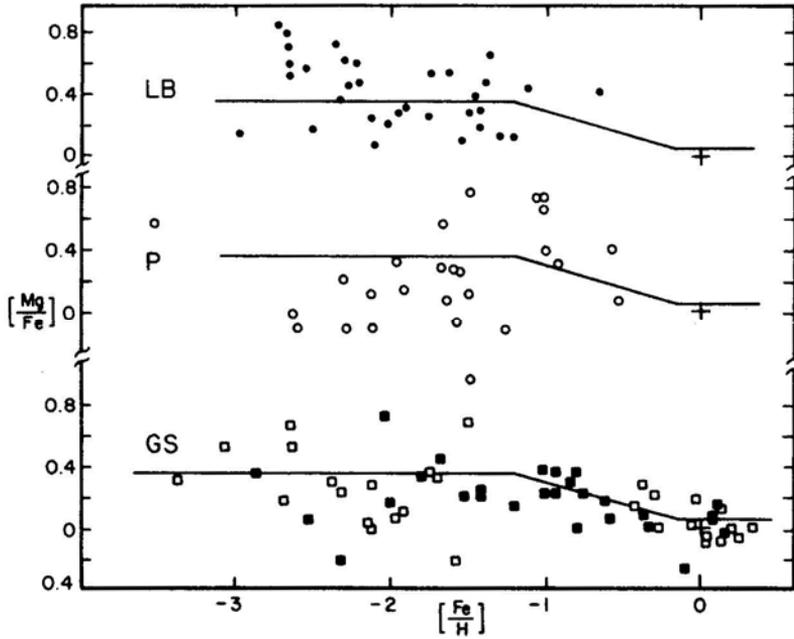


Figure 3. $[\text{Mg}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ for the samples analysed by LB, GS and Peterson (1981; hereinafter, P). Giants ($\log g < 3.0$) in GS's sample are denoted by open squares, and dwarfs and subgiants ($\log g \geq 3.0$) by filled squares. The identical lines drawn through the data are approximate fits based on data in Figs 2 and 5.

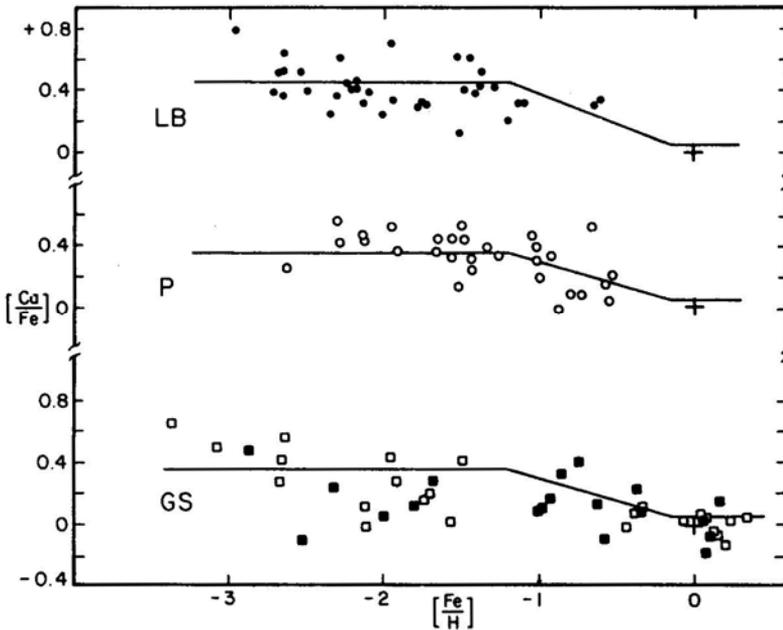


Figure 4. $[\text{Ca}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ for the samples analysed by LB, GS, and P. See caption to Fig. 3 for comments on the symbols and the lines.

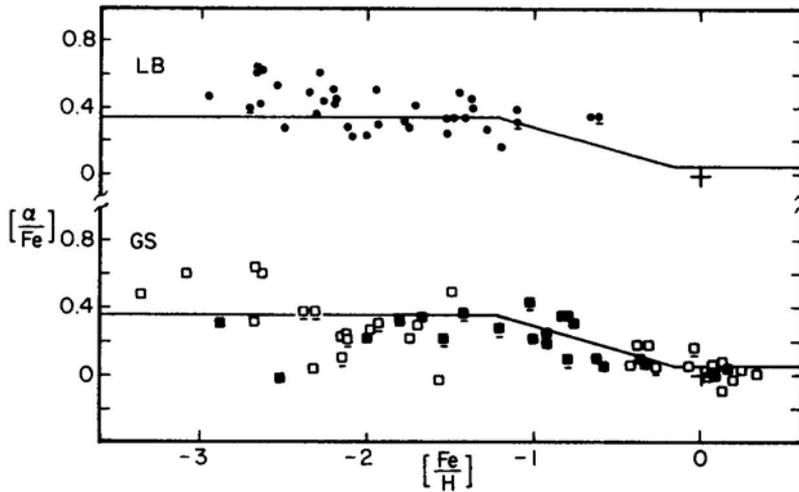


Figure 5. $[\alpha/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ for the samples analysed by LB and GS. See caption to Fig. 3 for comments on the symbols and the lines. The explanation of the underlined symbols is provided in the caption to Fig. 2.

scatter in $[\alpha/\text{Fe}]$ at $[\text{Fe}/\text{H}] \sim 0.0$. On the present evidence (Fig. 2), the scatter in $[\alpha/\text{Fe}]$ is less than about ± 0.03 dex, a value certainly dominated by the measurement errors, and A_α apparently differs from the mean $[\alpha/\text{Fe}]$ by an amount exceeding 0.03 dex. The remarkably small intrinsic scatter must constrain theories of stellar nucleosynthesis.

The increase of the α/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 31G 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 \AA mm^{-1} image-tube spectra providing the Mg I b lines in 111 dwarfs. For approximately 90 disc stars ($[\text{Fe}/\text{H}] > -1$), Laird's least-squares fit gives

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

The coefficient (-0.28) is identical to mine. The offset (my A_α) 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 $[\alpha/\text{Fe}] = A_\alpha$ at $[\text{Fe}/\text{H}] \sim -0.2$. For the halo ($[\text{Fe}/\text{H}] < -1$), Laird obtains a mean $[\alpha/\text{Fe}] = +0.24 \pm 0.13$ (s.d.) from 22 stars and, hence, to a 0.30 increase above the value at $[\text{Fe}/\text{H}] = 0.0$, an increase precisely equivalent to that given by our prescription.

Perhaps, the leading outstanding questions about the α/Fe ratio concern its behaviour in the halo. The simplest assumption consistent with most of the published abundances is that $[\alpha/\text{Fe}]$ is constant below $[\text{Fe}/\text{H}] \sim -1$ with an observed scatter which is small (say, ± 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 $[\alpha/\text{Fe}]$ according to GS is rather larger than assumed. The scatter is ± 0.4 dex in $[\text{Mg}/\text{Fe}]$ (Fig. 3) and ± 0.3 dex in $[\alpha/\text{Fe}]$ (Fig. 2).
2. LB's result show $[\alpha/\text{Fe}]$ to increase slightly in the extreme halo stars ($[\text{Fe}/\text{H}] < -2$) (Fig. 5).

An assumption that the intrinsic scatter in $[\alpha/\text{Fe}]$ for halo stars is small is not necessarily compatible with the theories of Galactic chemical evolution. If the α -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, $[\alpha/\text{Fe}]$ to show an increasing scatter with decreasing $[\text{Fe}/\text{H}]$. Also, halo stars now in the solar neighbourhood and having the same $[\text{Fe}/\text{H}]$ 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 $[\alpha/\text{Fe}]$ 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 $[\text{Si}/\text{Fe}]$ and $[\text{Mg}/\text{Fe}]$ for disc stars is insufficient to mask the trend with $[\text{Fe}/\text{H}]$, but the scatter in the halo suddenly and dramatically increases below $[\text{Fe}/\text{H}] \sim -1.5$. A dominant contributor to the scatter is the set of abundances based on CASPEC CCD-spectra. Infact, 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, Francois & Spite 1985). We suggest that the totality of present evidence does not demand that the scatter in $[\alpha/\text{Fe}]$ at a given $[\text{Fe}/\text{H}]$ 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 $[\alpha/\text{Fe}]$ in the halo increases either steadily with declining $[\text{Fe}/\text{H}]$ below $[\text{Fe}/\text{H}] \sim -1$ or more rapidly below $[\text{Fe}/\text{H}] \sim -2$ after remaining level between $[\text{Fe}/\text{H}] = -1$ and -2 . We offer this hint as an incentive to observers. By way of supporting evidence, we note that the $[\text{Fe}/\text{H}] \sim -2$ is also the point below which LB report a steady increase in $[\text{Ni}/\text{Fe}]$ (see also Luck & Bond 1983), and a slight decline in $[\text{Ti}/\text{Fe}]$. Other changes occur at or near this metallicity. There is a deficiency of *s*-process elements beginning near $[\text{Fe}/\text{H}] = -1.5$ (Spite & Spite 1978; Spite 1983, and LB). Carbon appears to increase in abundance relative to iron beginning at $[\text{Fe}/\text{H}] \sim -1.8$ (Tomkin, Sneden & Lambert 1986). There is contrary evidence on some of these changes. In particular, the $[\text{Ni}/\text{Fe}]$ trends have been challenged. Magain (1985) reports $[\text{Ni}/\text{Fe}] = +0.05$ for HD 19445 with $[\text{Fe}/\text{H}] = -2.33$, and $+0.08$ for HD 140283 with $[\text{Fe}/\text{H}] = -3.00$. LB's expected results for these stars are $[\text{Ni}/\text{Fe}] = +0.2$ 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 α -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}Na and ^{27}Al are the sole stable nuclides of these elements. Although ^{24}Mg and ^{28}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 instars 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 α -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:

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

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

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

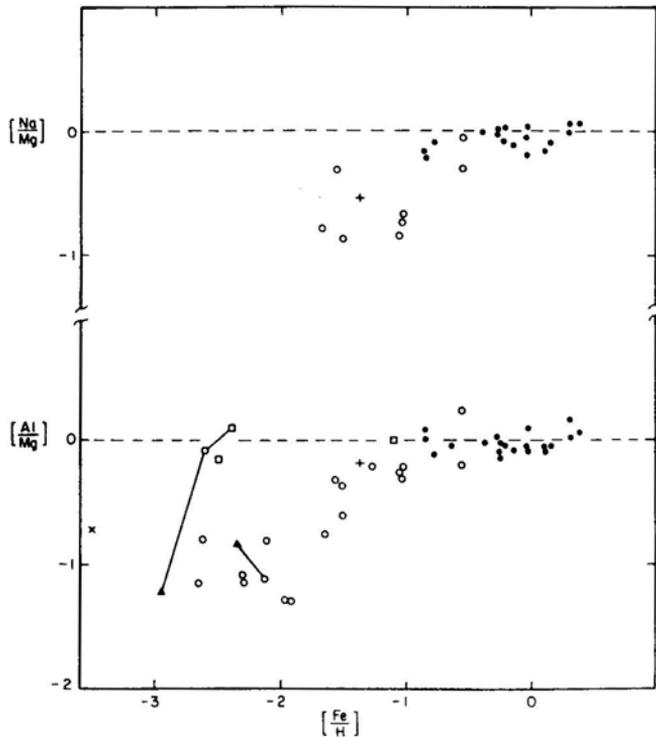


Figure 6. $[\text{Na}/\text{Mg}]$ and $[\text{Al}/\text{Mg}]$ as a function of $[\text{Fe}/\text{H}]$ for the F and G dwarfs analysed by TLB (filled circles) and others (open circles: Peterson 1981; open squares: Spite & Spite 1980; filled triangles: Arpigny & Magain 1983; plus sign: Tomkin & Lambert 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 $A_{\text{Al}} \simeq 0.0$. 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 I 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 $[\text{Al}/\text{Mg}] \simeq 0$ 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 α -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_{Al} (or A_{Na}) as the

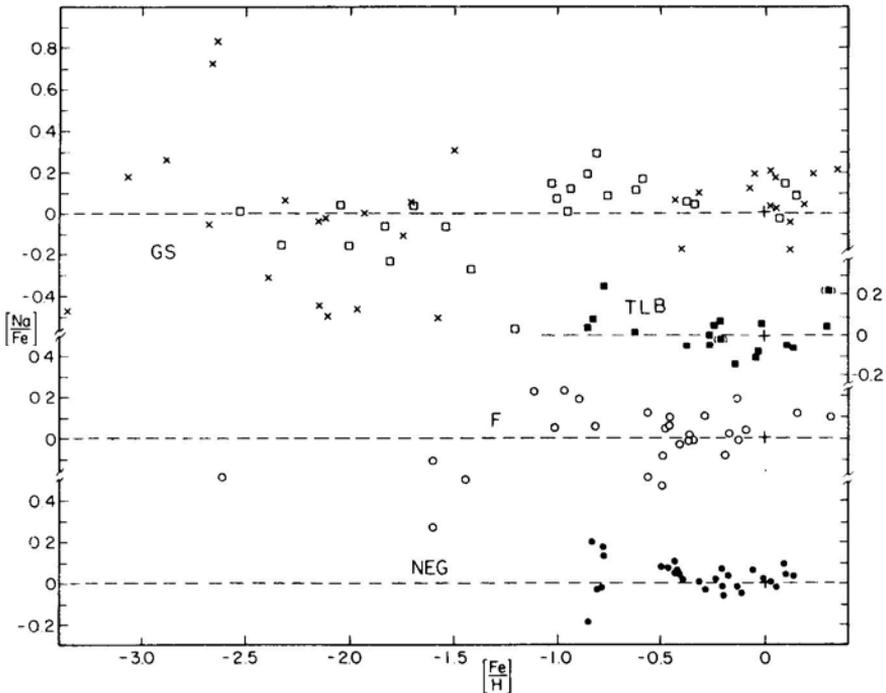


Figure 7. $[\text{Na}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ for the samples analysed by GS, TLB, F, and NEG. See caption to Fig. 1 for comments on the symbols.

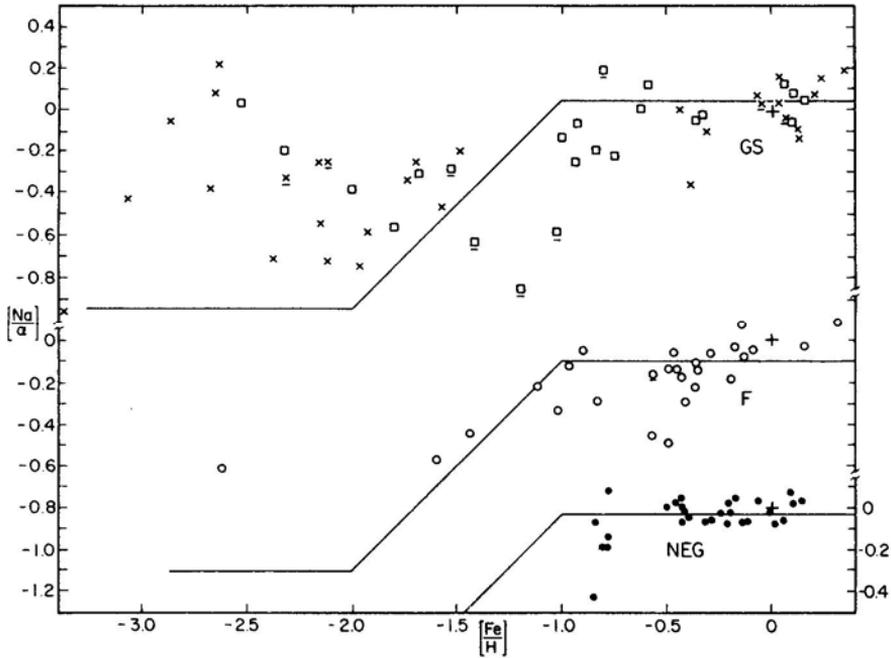


Figure 8. $[Na/\alpha]$ as a function of $[Fe/H]$ for the samples analysed by GS, F, and NEG. See captions to Figs 1 and 2 for comments on the symbols. The line fitted by eye to the points (the disc stars are emphasized here) is described in the text. It is an approximate fit to the points plotted in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

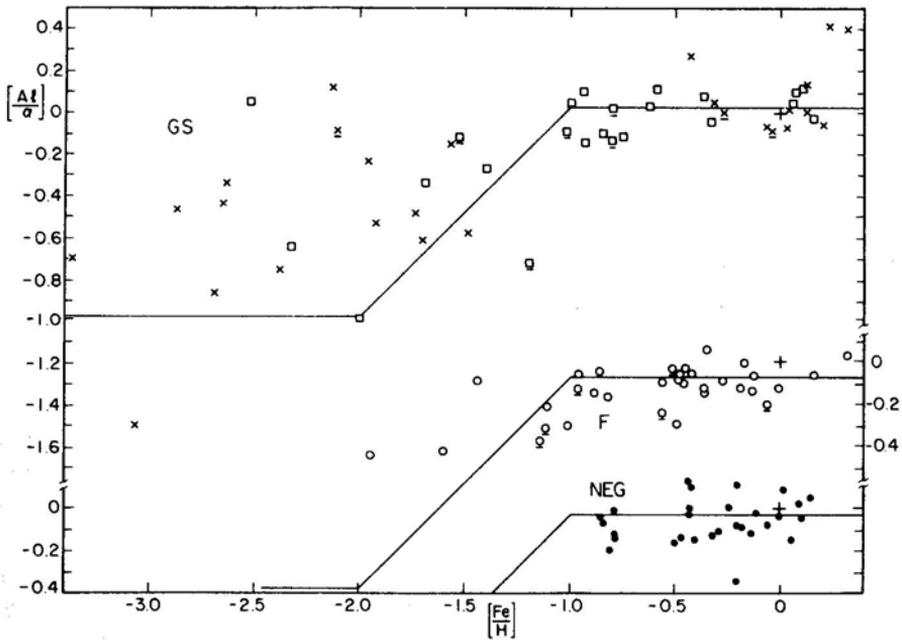


Figure 9. $[Al/\alpha]$ as a function of $[Fe/H]$ for the samples analysed by GS, F, and NEG. See caption to Fig. 8 for explanation of the symbols and the line.

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 ($[\text{Fe}/\text{H}] \geq -1$): $[\text{Na}/\alpha]$ and $[\text{Al}/\alpha]$ are independent of $[\text{Fe}/\text{H}]$. One cannot exclude a slight increase of the ratios with $[\text{Fe}/\text{H}]$, say by 0.1 dex between $[\text{Fe}/\text{H}]$ of -1 and 0 . The scatter in $[\text{Na}/\alpha]$ reported by GS and F is presumably attributable to measurement errors. Certainly, this scatter exceeds that exhibited by TLB's and NEG's samples. Frangois'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 $[\text{Fe}/\text{H}] \sim -2.5$ as the point below which $[\text{Al}/\alpha]$ and $[\text{Na}/\text{Mg}]$ 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 $[\text{Fe}/\text{H}] \leq -2.0$ 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 $[\text{Fe}/\text{H}] < -2.0$ 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 $[\text{Na}/\alpha]$ and $[\text{Al}/\alpha]$ 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 $-1.5 < [\text{Fe}/\text{H}] < -1.0$ which provide mean values of $[\text{Na}/\alpha] = -0.24$ and $[\text{Fe}/\text{H}] = -1.33$ (or $[\text{Na}/\alpha] = -0.34$ if one very discrepant star is dropped). These values fall close to the prescription. Two stars with $[\text{Fe}/\text{H}] < -2.0$ have $[\text{Na}/\alpha] > 0$ and apparently fall well above the prescription. For Al, the means in the same ranges are $[\text{Al}/\alpha] = +0.13$ (4 stars with a mean $[\text{Fe}/\text{H}] = -1.31$) and -0.37 (4 stars with a mean $[\text{Fe}/\text{H}] = -2.35$). The $[\text{Al}/\alpha]$ 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 , and -0.83 . These $[\text{Al}/\alpha]$ 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}Mg and ^{26}Mg abundances which were less than the solar/terrestrial values: $^{i}\text{Mg}/^{24}\text{Mg} < 7$ per cent, but $^{i}\text{Mg}/^{24}\text{Mg} = 13$ per cent for terrestrial samples (here ^{i}Mg denotes one of the heavier isotopes, *i.e.*, $i = 25$ or 26). Lambert & McWilliam (1986) set a lower limit to $^{i}\text{Mg}/^{24}\text{Mg} (\leq 3$ per cent) for the subgiant ν Ind with $[\text{Fe}/\text{H}] = -1.52$. Barbuy (1985) provides estimates of ^{i}Mg for a

selection of (mainly) metal-poor dwarfs and giants. McWilliam & Lambert (1986) rediscuss stars first analysed by Tomkin & Lambert (1980).

In Fig. 10, I show currently available results for ${}^i\text{Mg}/{}^{24}\text{Mg}$ versus $[\text{Fe}/\text{H}]$ 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 ${}^i\text{Mg}/\text{Mg}$ at a given $[\text{Fe}/\text{H}]$ is probably dominated by observational errors. The decline in ${}^i\text{Mg}/\text{Mg}$ may begin at a higher metallicity than is evident in the $[\text{Na}/\alpha]$ and $[\text{Al}/\alpha]$ results. Arnett's (1971) calculations of explosive nucleosynthesis predict the more rapid decline for ${}^i\text{Mg}/\text{Mg}$: $[\text{Na}/\text{Mg}]$ and $[\text{Al}/\text{Mg}]$ 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 $[\text{Al}/\text{Mg}]$ should be tightest when plotted against $[(\text{C} + \text{N} + \text{O})/\text{H}]$ rather than either $[\text{Mg}/\text{H}]$ or $[\text{Fe}/\text{H}]$; 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 $[\text{Al}/\text{Fe}]$ is plotted against $[\text{Fe}/\text{H}]$ shows that Al and Fe are synthesized in rather different sites.)

In summary, the variation of odd-even nuclei relative to the α -nuclei through the disc

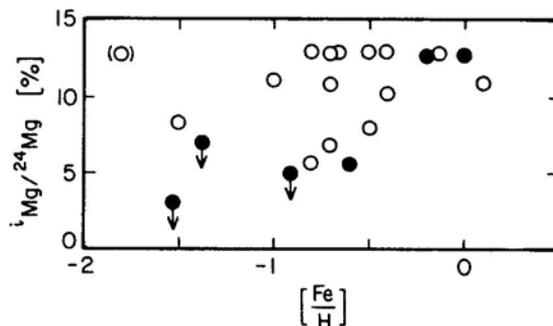


Figure 10. ${}^i\text{Mg}$ isotopic abundances as a function of $[\text{Fe}/\text{H}]$. Observations (here ${}^i\text{Mg} = {}^{25}\text{Mg}$ or ${}^{26}\text{Mg}$) are taken from Barbuy (1985—open circles) and Tomkin & Lambert (1980), Lambert & McWilliam (1986), and McWilliam & Lambert (1986)—solid symbols for the latter three references. The symbol in parentheses is based on a spectrum described as 'bad' by Barbuy.

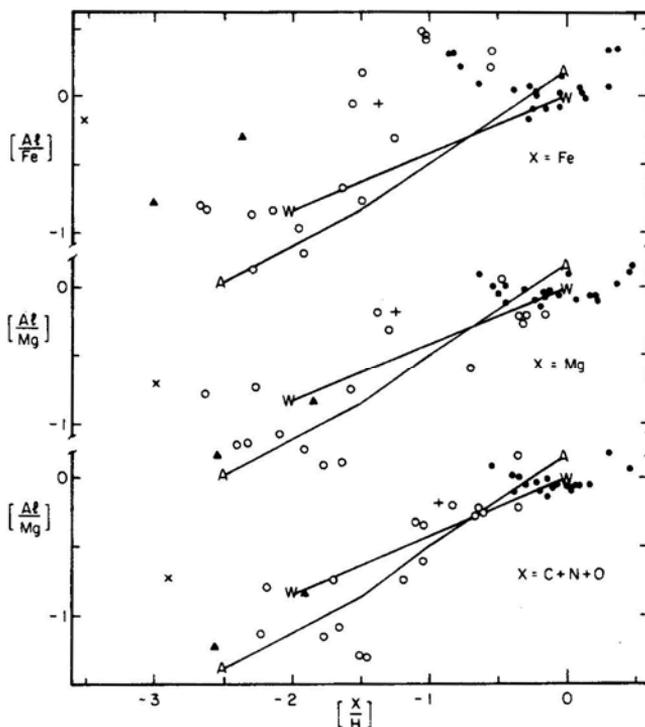


Figure 11. Aluminium in the halo and disc. The three plots show $[Al/Fe]$ versus $[Fe/H]$ (top), $[Al/Mg]$ versus $[Mg/H]$ (middle), and $[Al/Mg]$ versus $[(C+N+O)/H]$ (bottom). The key to the observations is given in the caption to Fig. 6. Theoretical predictions are by Arnett (1971; lines terminated 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 α -nuclei (Mg, Si, Ca), the odd-even nuclei (Na, Al—see Fig. 13 where $[\text{odd-even}/\alpha]$ 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

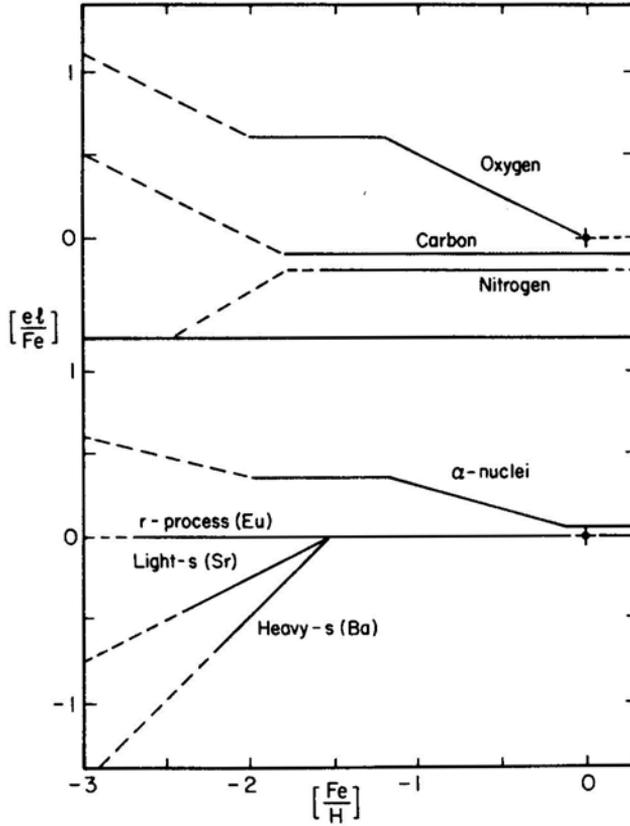


Figure 12. $[e/Fe]$ as a function of $[Fe/H]$ for C, N, O, α -nuclei (Mg, Si, Ca), and s - and r -process nuclei. Observed trends are represented here by connected straight lines with broken lines denoting uncertainty because the observations are sparse or less accurate.

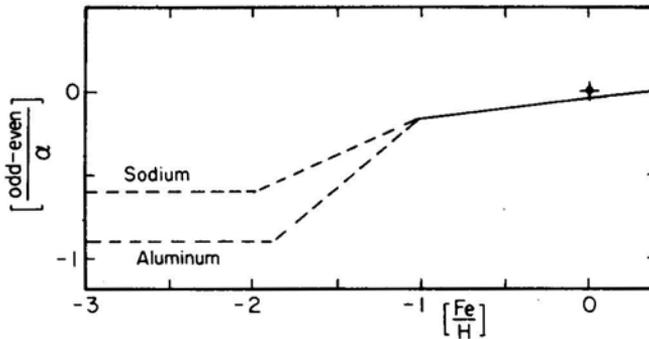


Figure 13. $[odd-even/\alpha]$ as a function of $[Fe/H]$ for Na and Al. See caption for Fig. 12.

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 $[\text{Fe}/\text{H}] = 0$; 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 ($[\text{Ni}/\text{Fe}] > 0$ for $[\text{Fe}/\text{H}] < -2$) and Ti ($[\text{Ti}/\text{Fe}]$ declines for $[\text{Fe}/\text{H}] < 2$)—see LB.

In the variation of $[\text{el}/\text{Fe}]$ with $[\text{Fe}/\text{H}]$, 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 $[\text{Fe}/\text{H}] = -1.2 \pm 0.1$, 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 $[\text{Fe}/\text{H}] = -0.2 \pm 0.1$ in the α -nuclei plots. Oxygen may show a change of slope at a slightly higher metallicity, say $[\text{Fe}/\text{H}] = 0.0$. In the extreme halo, $[\text{Fe}/\text{H}] \sim -2$ 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 $[\text{Fe}/\text{H}] \lesssim -2$.

For Na and Al, $[\text{el}/\alpha]$ 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 $[\text{Fe}/\text{H}]$. 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 $[\text{odd-even}/\alpha] \sim 0.0$ for $[\text{Fe}/\text{H}] < -2$. The evidence that $[\text{Na}/\alpha] > [\text{Al}/\alpha]$ in the extreme halo is weak. For $[\text{Fe}/\text{H}] > -1$, I show $[\text{odd-even}/\alpha]$ to increase with $[\text{Fe}/\text{H}]$, but the evidence for this is inconclusive; $[\text{odd-even}/\alpha] \sim 0.0$ 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

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

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

$$\left[\frac{\text{el}}{\text{Fe}} \right] = \left[\frac{\text{Fe}}{\text{H}} \right].$$

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 ($[\text{C}/\text{Fe}] \sim 0$), simple models predict

$$\left[\frac{\text{N}}{\text{Fe}} \right] = \left[\frac{\text{Fe}}{\text{H}} \right].$$

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 $[\text{N}/\text{Fe}] = 0$.

Inspection of Fig. 12 shows that

$$\left[\frac{\text{N}}{\text{Fe}} \right] \sim \left[\frac{\text{N}}{\text{C}} \right] \sim 0 \quad \text{and} \quad \left[\frac{\text{N}}{\text{O}} \right] \leq \left[\frac{\text{O}}{\text{H}} \right]$$

for nitrogen in disc stars. The first relations suggest that N is a 'primary' element relative to C, Fe, and many other elements showing $[\text{el}/\text{Fe}] \sim 0$. 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 $[\text{O}/\text{H}] \sim 0.5$ $[\text{Fe}/\text{H}]$ and $[\text{N}/\text{Fe}] \sim 0$.

This last discussion shows that a classification of elements as 'primary' or 'secondary' must involve more than the inspection of plots of $[\text{el}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$. 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

$$\left[\frac{s}{\text{O}} \right] = \left[\frac{\text{O}}{\text{H}} \right]$$

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 $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$ reaction, where the ^{22}Ne is synthesized by the chain

$^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^+, \gamma)^{18}\text{O}$ (α, γ) ^{22}Ne , and the ^{14}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 $[s/\text{O}]$ rather than $[s/\text{Fe}]$. In the absence of infall of metal-poor gas, standard relations predict

$$\left[\frac{s}{\text{O}} \right] = \left[\frac{\text{O}}{\text{H}} \right].$$

This is, in fact, the observed relation for $[\text{Fe}/\text{H}] \gtrsim -1.5$ (see above and Fig. 12).

A third example of possible dual assignment of 'primary' and 'secondary' is Na or Al where $[\text{Na}/\text{Fe}] \sim [\text{Al}/\text{Fe}] \sim 0$ with considerable scatter, a result earning Na and Al the label 'primary'. But as we showed with Fig. 11, $[\text{Na}/\text{Mg}]$ and $[\text{Al}/\text{Mg}]$ are better correlated with $[(\text{C} + \text{N} + \text{O})/\text{H}]$ 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, $[s/\text{Fe}]$ would have constant negative value in the halo (the limited observations do not yet exclude this possibility for $[\text{Fe}/\text{H}] \lesssim -2.5$). The stars examined in detail by Sneden and colleagues have $[\text{Fe}/\text{H}] = -2.6$ 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.

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References

- Arnett, W. D. 1971, *Astrophys. J.*, **166**, 153.
- Arpigny, C., Magain, P. 1983, *Astr. Astrophys.*, **127**, L7.
- Barbuy, B. 1985, *Astr. Astrophys.*, **151**, 189.
- Bell, R. A., Branch, D. 1970, *Astrophys. J.*, **5**, L203.
- Bell, R. A., Eriksson, K., Gustafsson, B., Nordlund, Å., 1976, *Astr. Astrophys. Suppl Ser.*, **23** .37.
- Bessell, M. S., Norris, J. 1982, *Astrophys. J.*, **263**, L101.
- Boesgaard, A. M. 1968, *Astrophys. J.*, **154**, 185.
- Carney, B. W., Peterson, R. C. 1981, *Astrophys. J.*, **245**, 238.
- Cayrel de Strobel, G., Bentolila, C., Hauck, B., Duquennoy, A. 1985, *Astr. Astrophys. Suppl. Ser.*, **59**, 145.
- Clegg, R. E. S., Lambert, D. L., Tomkin, J. 1981, *Astrophys. J.*, **250**, 262 (CLT).
- Francois, P. 1986, *Astr. Astrophys.*, in press (F).
- Francois, P. 1986, preprint.
- Gratton, R. G., Sneden, C. 1986, preprint (GS).
- Gustafsson, B., Bell, R. A., Eriksson, K., Nordlund, Å. 1975, *Astr. Astrophys.*, **42**, 407.
- Holweger, H., Müller, E. A. 1974, *Solar Phys.*, **39**, 19.
- Iben, I., Jr., Truran, J. W. 1978, *Astrophys. J.*, **220**, 980.
- Kraft, R. P. 1987, *J. Astrophys. Astr.*, **8**, 89.
- Laird, J. B. 1986, *Astrophys. J.*, **303**, 718.
- Lambert, D. L., McWilliam, A. 1986, *Astrophys. J.*, **304**, 436.
- Luck, R. E., Bond, H. E. 1983, *Astrophys. J.*, **271**, L75 (LB)
- Luck, R. E. 1985, *Astrophys. J.*, **292**, 559.
- Magain, P. 1985, *Astr. Astrophys.*, **146**, 95.
- McWilliam, A., Lambert, D. L. 1986, in preparation.
- Nissen, P. E., Edvardsson, B., Gustafsson, B. 1985, in *Production and Distribution of C: N, O Elements*, Eds I. J. Danziger, F. Matteucci & K. Kjär, ESO, Garching, p. 131 (NEG).
- Peterson, R. C. 1981, *Astrophys. J.*, **244**, 989(P).
- Sneden, C., Parthasarathy, M. 1983, *Astrophys. J.*, **267**, 757.
- Sneden, C., Pilachowski, C. A. 1985, *Astrophys. J.*, **288**, L55.
- Sotirovski, P. 1971, *Astr. Astrophys.*, **14**, 319.
- Spite, F. 1983, *Mem. Soc. astr. Ital.*, **54**, 283.
- Spite, F., Francois, P., Spite, M. 1985, *The Messenger*, No. 42, p.14.
- Spite, M., Spite, F. 1978, *Astr. Astrophys.*, **67**, 23.
- Spite, M., Spite, F. 1980, *Astr. Astrophys.*, **89**, 118.
- Tinsley, B. M. 1979, *Astrophys. J.*, **229**, 1046.
- Tomkin, J., Lambert, D. L. 1976, *Astrophys. J.*, **208**, 436.
- Tomkin, J., Lambert, D. L. 1979, *Astrophys. J.*, **227**, 209.
- Tomkin, J., Lambert, D. L. 1980, *Astrophys. J.*, **235**, 925.
- Tomkin, J., Lambert, D. L. 1984, *Astrophys. J.*, **279**, 220.
- Tomkin, J., Lambert, D. L., Balachandran, S. 1985, *Astrophys. J.*, **290**, 289 (TLB).
- Tomkin, J., Sneden, C., Lambert, D. L. 1986, *Astrophys. J.*, **302**, 415.
- Truran, J. W. 1981, *Astr. Astrophys.*, **97**, 391.
- Truran, J. W., Iben, I., Jr., 1977, *Astrophys. J.*, **216**, 797.
- Wallerstein, G. 1962, *Astrophys. J. Suppl Ser.*, **6**, 407.
- Woosley, S. E., Weaver, T. A. 1982, in *Essays in Nuclear Astrophysics*, Eds C. A. Barnes, D. D. Clayton & D. N. Schramm, Cambridge University Press, p. 377.

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 α -elements Mg, Si, and Ca; *i.e.*, [K/Fe] increases with decreasing metallicity to reach [K/Fe] \sim 0.4 for [Fe/H] $<$ -1. Potassium with stable isotopes ^{39}K and ^{41}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 α (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 α -elements, the mean abundances for this sample in which all stars belong to the halo (the most metal-rich star has [Fe/H] = -0.87) are [Mg/Fe] = 0.43 ± 0.02 (17 stars), [Si/Fe] = 0.39 ± 0.05 (8 stars), and [Ca/Fe] = $+0.50 \pm 0.04$ (14 stars). The mean values do not differ sensibly when the sample is divided at [Fe/H] = -2. Gratton & Sneden's sample of 13 extremely metal-poor stars ([Fe/H] \leq -1.3) yields the following mean values: [Mg/Fe] = 0.34 ± 0.03 , [Si/Fe] = 0.50 ± 0.06 , and [Ca/Fe] = 0.31 ± 0.09 . (I give the formal errors of the mean values.) Magain's reanalysis of published data suggests that the α -elements (relative to Fe) are slightly more abundant than any recommended trend would suggest, and confirms my suggestion that the scatter in [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 [Fe/H]. More importantly, his results do not support my tentative suggestion that [α /Fe] may increase again in the extreme halo ([Fe/H] $<$ -2).

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

The papers by Francois have now appeared in print: *Astr. Astrophys.*, **160**, 264 (F), and *Astr. Astrophys.*, **165**, 183.