Light Element Abundances in F Stars and the Chemical Evolution of the Galactic Disk

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Summary

A project for investigation of the evolution of the chemical elements in the galactic disk, and in particular of the elements in the third and fourth period of the periodic table, is presented. Chemical abundances of F dwarfs of different ages and of different overall metal abundance are used for this purpose. Preliminary results for 15 stars are reported; they indicate abundance ratios of O, Mg, Si, Ca and Ti relative to iron that are systematically greater than the solar ratio for stars with [Fe/H] < -0.5 and with the excess increasing with decreasing [Fe/H] and decreasing atomic number. An odd-even effect for the sequence Na, Mg, Al, Si is found for the metal-poor disk stars.

Introduction

The history of the chemical elements in our Galaxy is still known only fragmentarily. Man pieces are left to be put into the puzzle, and as yet we can do little but guess what the final picture will look like. More systematic observational investigations are necessary before a number of fundamental questions can be answered (the answers will however have bearings far beyond the problems of the chemical evolution of the Galaxy): In which objects were the first heavy elements formed; massive supernovae of about 25 $M_{\odot}$, very massive ones (100–300 $M_{\odot}$, so-called hypernovae), or still heavier supermassive stars? What is the importance in nucleosynthesis of Type I supernovae – do they produce most of the iron-group elements? Which is the role played by infall of intergalactic gas during the disk evolution? Are there bursts of star formation in the disk? Does the initial mass function (IMF) vary significantly with time from the halo phase to the disk phase or even during the disk phase? Is the IMF a function of radial distance from the centre of the Galaxy? And so on.

For the study of the chemical evolution of the galactic disk it would be important to investigate the initial chemical composition of stars of different well-known ages and with different kinematical properties. Thanks to the power of the Strömgren photometric uvbyβ system, the modern coudé scanners, such as the ESO CAT/CES, and the astrophysical properties of F dwarfs, it is possible today to make a first systematic attempt in this direction.

The F dwarfs are suitable for a study of the history of the galactic disk for several reasons: their ages range all the way up to 10^{10} years and these ages may be determined with the uvbyβ photometry, by measuring the effective temperature and the distance of the star from the zero age main sequence. For somewhat evolved stars an accuracy of about 0.2 dex in the age can be achieved in this procedure, with major sources of errors being due to the uncertain mixing length parameter and helium abundance as well as other possible more fundamental errors in the stellar-structure calculations. The chemical composition of the atmospheres of F dwarfs is not thought to be affected by the nuclear reactions in the cores of the stars, nor should it for most stars be affected by gravitational diffusion or selective radiative pressure, since the convective motions in the stellar envelopes should prevent these separation mechanisms from playing any important rôle. Thus, the atmospheres of most F dwarfs may be taken as samples of the chemical composition of the interstellar matter from which the stars were once formed. Furthermore, suitable absorption lines of many chemical elements can be found in F dwarf spectra. The stars are also close enough to the Sun in the HR diagram for making it reasonable that the interpretation of line strengths in terms of chemical abundances relative to solar abundances may be reliable, since the errors in the model atmospheres should cancel to a great extent in a differential study relative to the Sun.

It is of considerable interest to explore the abundance of the elements lighter than iron as a part of a study of the evolution of the Galaxy. The well established overabundance of oxygen in halo stars by about a factor of four relative to iron (as compared to the Sun) was shown by Clegg et al. (1981) to be significant also in the old disk stars – not until the overall metal abundance approached the solar value at a rather late stage in the evolution of the disk the oxygen-to-iron ratio became solar. Twarog and Wheeler (1982) explained the oxygen overabundance as a result of a more efficient oxygen production in the early nucleosynthesis than in the late disk evolution, as compared with the production of iron. In fact, evolutionary calculations for massive pre-supernovae have demonstrated that the outer layers of these objects should be rich in oxygen produced during helium burning (Arnett 1978) and the discovery of several oxygen-rich supernovae remnants has verified this (Trimble 1983, and references given therein). It may be reasonable to assume that such massive supernovae are responsible for the oxygen overabundance of Pop II, and that the oxygen-rich/iron-poor gas produced continued to affect the composition of the early disk due to the continued infall of this halo gas onto the disk. It is of great interest to study the abundances of "α-elements" such as Mg, Si, Ca and Ti, to see whether similar overabundances as a function of metal abundance can be traced for these elements; that would not agree with the predicted smaller relative enhancements in the pre-supernovae models of Woosley and Weaver (1982 a, b). The "odd" elements (Na, Al, P, K, Sc) were predicted in some theoretical scenarios (Arnett 1971, Truran and Arnett 1971) to be less abundant, relative to the α-elements, in metal-poor stars. These odd-even effects have been looked for by several investigators with very few definite results. E.g. Tomkin, Lambert and Balachandran (1984) find a considerable scatter in their plot of [Al/Mg] versus [Mg/H] for halo and disk stars. The Al abundance, e.g., relative to the Mg abundance, is important as a measure of the initial composition of the site of nucleosynthesis, since the Al production is controlled by the neutron excess of the parent nuclei.

Most investigations of the evolution of the abundances of the light elements in the Galaxy have been confined to the study of the relations between the abundance of any element X, [X/H] vs. [Fe/H] (the square brackets as usual denoting the logarithmic abundances relative to the Sun), and the iron abundance or the overall metal abundance has been adopted as a measure of time. However, there are several indications that the metal abundance is not a well-defined monotonic function of time in the Galaxy, i. e., the mixing of the interstellar gas is not complete enough for producing a homogeneous

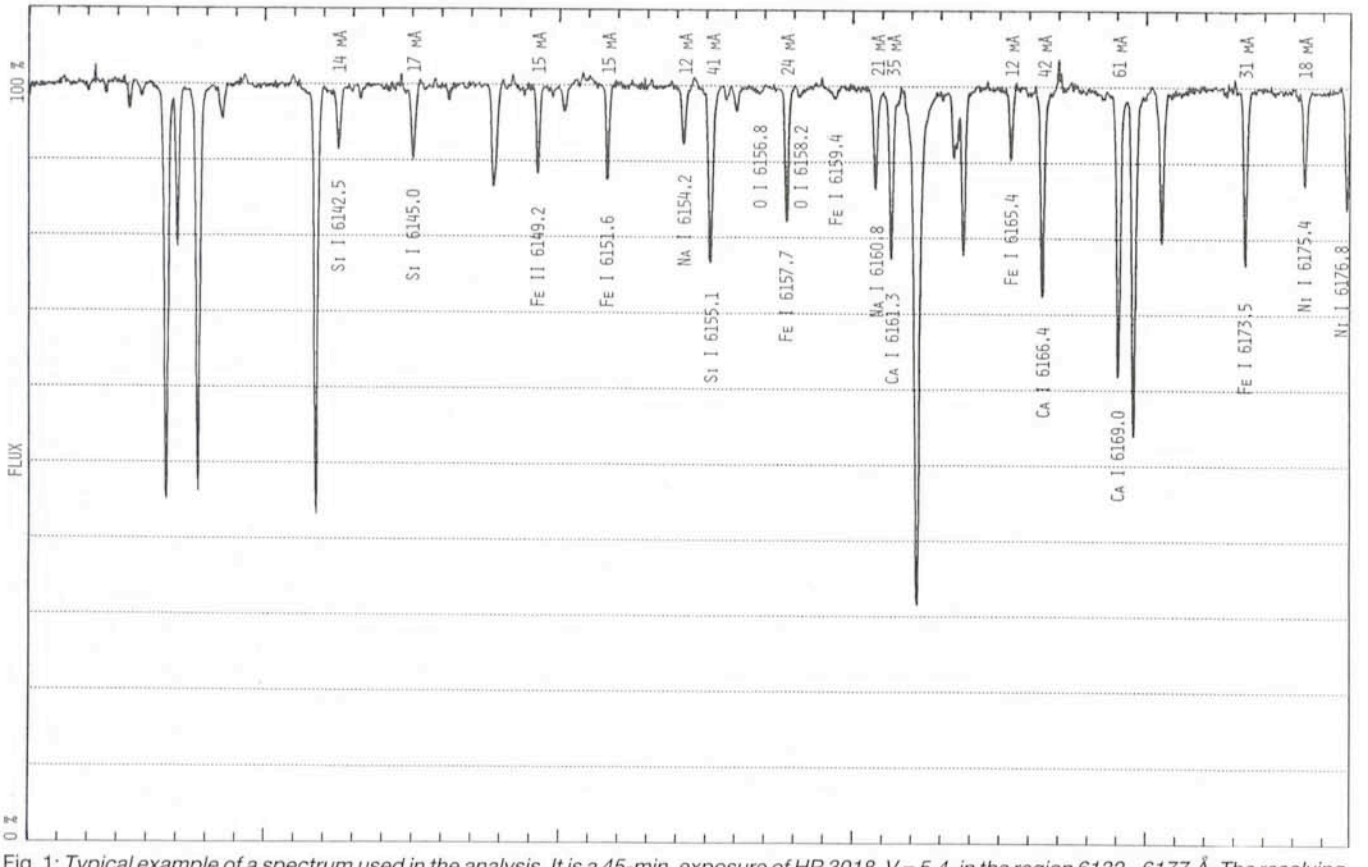

Fig. 1: *Typical example of a spectrum used in the analysis. It is a 45-min. exposure of HR 3018, V = 5.4, in the region 6132–6177 Å. The resolving power is 100,000. The lines used in this region are identified, and the equivalent widths measured and used for this spectrum are indicated.*

interstellar medium at a given time. Traces of chemical gradients and inhomogeneities in the Galaxy can be found in the composition of stars from relatively recent epochs, and we have certainly no good reason to expect these phenomena to be less important in the early epochs of the Galaxy and of its disk. From this point of view it is important to combine the abundance information with independent age information and kinematic information for the stars. Use of this additional information in attempts to study the detailed chemical composition, e.g., as a function of [Fe/H], age or eccentricity of the galactic orbit, requires a well-defined statistical approach and a large sample of stars. The present study is a progress report from a study of this systematic character.

In order to minimize unknown selection effects we have sampled our programme stars from the complete uvbyβ survey catalogue of F stars by Erik Heyn-Olsen (see Olsen 1983). The photometry gives independent information on effective temperatures from the reddening-free β index and the b-y colour (the present stars are within 50 pc and thus practically unreddened), log g from the δc_1 index (and rather good age estimates for stars with $\delta c_1 > 0\overset{\mathrm{m}}{.}040$) and [Fe/H] from the δm_1 index. We have subdivided the 13,000 stars in the catalogue into nine sub-groups of δm_1, i.e. according to overall metal abundance, and we shall observe the approximately 30 brightest stars in each group. We have excluded known binaries and peculiar stars, partially guided by the results of a CORAVEL study of all programme stars.

The northern stars are being observed at the McDonald Observatory by D. Lambert and J. Tomkin and the southern stars by the present authors at ESO. The final analysis will be performed jointly by the two groups. The 150 southern stars, observed and analysed in collaboration with J. Andersen, Copenhagen University Observatory, are distributed uniformly over the hemisphere, and are brighter than about $6\overset{\mathrm{m}}{.}0$ for the more metal-rich groups. For the most extreme – and rare – metal-poor stars the apparent-magnitude limit is $7\overset{\mathrm{m}}{.}0$.

Observations and Reductions

Spectra in five wavelength regions are obtained for each programme star; for the southern stars this is done with the ESO 1.4 m CAT telescope, the Coudé Echelle Spectrograph, and an 1,870 channel RETICON detector. The resolving power is about 80,000 and typically a signal-to-noise ratio of about 100 is obtained for each channel. The channel width is 23 to 37 mÅ, depending of wavelength region, which makes the spectrum oversampled by a factor of about 3. The reductions of the ESO spectra obtained until now have been carried out with the ESO IHAP system in Garching and Uppsala, and the equivalent widths were measured by fitting Gaussians to the line profiles with the convenient PHYS code written at Uppsala by several astronomers. Only lines with equivalent widths between 5 and 100 mÅ are used in order to reduce problems in measuring and with the theoretical damping treatment. The main emphasis is on spectral lines on the linear part of the curve of growth, with equivalent widths less than about 50 mÅ and thus relatively unaffected by microturbulence. For each individual line the Gaussian fit is checked by eye and the line is rejected if the fit is found too poor. In further attempts to avoid erroneous measures the line is also rejected if the FWHM measure is found to be unreasonable compared to those of other lines. The equivalent widths refer to a continuum defined by a number of narrow regions in each spectrum, selected to be free of lines in the Solar and Procyon spectra.

A typical spectrum is shown in Fig. 1 of the star HR 3018, V = 5.4. This star was independently observed by two observers, in two wavelength regions, at two different occasions, with two different RETICON arrays, and the spectra have been inde-

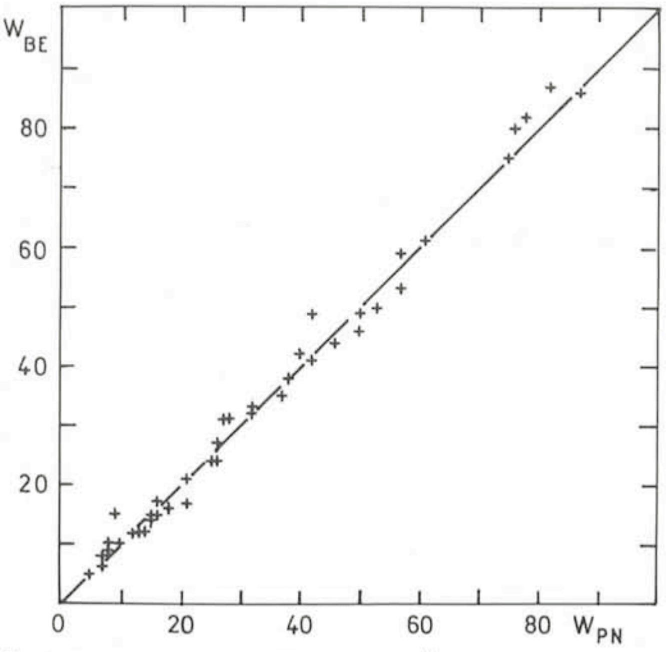

Fig. 2: *Comparison of equivalent widths (in mÅ) obtained from two sets of spectra of HR 3018 (one shown in Fig. 1) taken by two observers, using two different Reticon arrays. The spectra were separately measured and reduced by the two observers. The mean difference is 0.3 mÅ with a standard deviation of 2.6 mÅ for one measure.*

pendently reduced and measured by the two observers. The equivalent widths are compared in Fig. 2, where the lines between 5 and 100 mÅ are compared. The mean difference is 0.3 mÅ with a standard deviation of 2.6 mÅ for a single line. From this we conclude that it is possible to obtain very accurate equivalent widths with the present instrumentation.

Data on the five wavelength regions and on the elements studied in each region are given in Table 1.

Table 1: Wavelength regions

The 5105 Å region is not used here because the present study is made relative to the Sun and no observations of the solar spectrum are yet available for that region with the present equipment. Except for Fe II 6149.23 Å and Ba II 5853.68 Å all lines measured so far are lines of neutral elements.

Region	Range (Å)	Elements	Comm.
5105	5085–5125	Ti, Cr, Fe, Co, Ni, Y	Not used
5860	5840–5880	Ca, Ti, Fe, Ni, Ba	14 lines
6155	6130–6180	O, Na, Si, Ca, Fe, Ni	18 lines
7772	7740–7805	O, Si, Fe, Ni	12 lines
8746	8715–8780	Mg, Al, Si, Fe	9 lines

The lines are carefully selected to be free from hidden blends; of 101 candidate lines in the four last regions of Table 1 only 53 were finally included in the analysis.

Analysis

The abundance analysis is based on the assumption of LTE; however, the effects of departures from LTE on the abundances are being studied theoretically (cf. Saxner 1984) and observationally (see below). The models used in the analysis are blanketed and convective model atmospheres calculated with an updated version of the programme presented in Gustafsson et al. (1975), cf. Nissen and Gustafsson (1978). The models are individually calculated for each star using model parameters T_{eff}, log g, and overall metal abundance [M/H], derived from Strömgren photometry. The microturbulence parameter was derived as a function of the fundamental parameters in accordance with Nissen (1981). In Table 2 we give identifications, spectral type, V magnitude, model parameters from Strömgren photometry and derived iron abundance for the 15 stars investigated until now.

Table 2: The programme stars

			Parameters obtained from uvbyβ photometry					
HR	Name	Sp. type	V	T_{eff}	log g	[M/H]	ξ_t	[Fe/H]
33	6 Cet	F7V	4.9	6320	4.1	−0.5	1.8	−0.34
1545		F5V	6.3	6550	4.1	−0.4	1.8	−0.34
1983	γ Lep	F6V	3.6	6450	4.3	−0.1	1.6	−0.05
2883		F5V	5.9	6080	4.2	−0.7	1.5	−0.71
2906		F6IV	4.5	6250	4.1	−0.2	1.7	−0.16
2943	α CMi	F5IV-V	0.4	6840	4.1	+0.1	2.0	+0.04
3018		G0V	5.4	5890	4.4	−0.7	1.2	−0.78
3578		F6V	5.9	6060	4.4	−0.7	1.4	−0.82
4540	β Vir	F9V	3.6	6180	4.2	+0.1	1.6	+0.14
4657		F5V	6.1	5940	4.4	−0.7	1.2	−0.95
4989		F7IV	4.9	6400	4.2	−0.4	1.6	−0.24
5019	61 Vir	G6V	4.7	5580	4.3	+0.2	1.3	−0.03
5338	ι Vir	F6III	4.1	6240	4.0	−0.2	1.9	−0.09
6445	ξ Oph	F1III-IV	4.4	7010	4.2	−0.1	1.9	−0.13
HD22879		F9V	6.7	5920	4.3	−0.9	1.3	−0.85

The abundance analysis is made differentially to the Sun, with oscillator strengths determined from the solar flux spectrum, the reflected light of the Sun being observed with the same instrumentation as the one used for the stars.

Systematic errors in the abundances would result from errors in the effective temperature scale, in the surface gravities and in the microturbulence parameters. We estimate that errors in these fundamental parameters could amount to, at most, 100K (cf. Saxner and Hammarbäck, 1984), 0.2 dex and 0.2 km/s respectively, leading to errors in the abundances relative to hydrogen smaller than 0.05 dex. One exception is the oxygen abundance which is more temperature and gravity sensitive, since it is mostly neutral – the errors on [O/Fe] may well amount to 0.1 dex. Since our only line of barium is fairly strong, the abundance of this element is also sensitive to the microturbulence parameter – an error of 0.2 km/s corresponds to 0.1 in [Ba/Fe].

In a recent study, based on non-LTE calculations, Saxner (1984) has shown that iron is likely to be overionized in the transparent atmospheres of the metal-deficient F stars. If real, such a tendency should show up as a negative slope in Fig. 3a, unless it is masked by some other systematic error. Only for the most metal-deficient star, signs of an overionization may be seen in Fig. 3; a correction of an isolated iron-overionization effect would move it in the direction of the arrow in Fig. 3a. Further theoretical studies of the O, Na, Mg, Al and Si ionization equilibria in F stars are being planned.

The convection zone in the model atmospheres of F stars reaches rather shallow optical depths, and in real stars, the effects of convection are probably more important than the mixing-length recipe in the calculations indicates. A study of the uncertainties caused by convective energy transport, convective motions and convective inhomogeneities on our results must await detailed numerical simulations, similar to those of Nordlund (1978, 1982) for the Sun. In particular one should note the risk for even more pronounced non-local excitation and ionization as a result of thermal inhomogeneities, especially in metal-poor atmospheres. We hope to include a detailed study on possible errors due to convection in our final paper on the present subject.

Tomkin, Lambert and Balachandran (1984, TLB below) have recently determined abundances of light elements for F stars, and they have two stars in common with the present paper.

The resulting abundances relative to hydrogen differ from those obtained by us by less than 0.06 dex, except for [Na/H] and [Al/H] for HR 4540 which deviate by 0.09 and 0.07, respectively.

Results, Discussion and Conclusions

The results presented here for a small number of stars are preliminary and include data from only four of the five selected wavelength regions. In Fig. 3 values of [X/H] are plotted against [Fe/H] for X = O, Na, Mg, Al, Si, Ca, Ti, Ni and Ba in an attempt to trace possible evolutionary trends in the abundances relative to iron. The tendencies found here for the elements O, Mg, Al, Ca, Ti to be overabundant relative to iron for stars with [Fe/H] < -0.5 confirm the results of TLB for F stars and also agree well with those of Luck and Bond (1984) for more evolved stars. It is of interest to decide whether this increase of [X/Fe] with decreasing [Fe/H] is gradual and starts already at [Fe/H] ~ 0.0 (as suggested by the results of Luck and Bond) or whether it sets in more abruptly around [Fe/H] ~ -0.5 for elements heavier than oxygen. Fig. 3 suggests the latter to be the case for Mg and Fe. Thus, disk abundances with roughly solar abundance ratios relative to iron seem to have been established at a rather early epoch in the evolution of the Galaxy. More observations of stars with [Fe/H] ~ -0.5 are necessary to firmly verify this suggestion, which has bearings on when the IMF of the halo phase changed to the present day IMF and on the importance of infall of gas during the early disk evolution.

The slope found in the relations between [X/Fe] and [Fe/H] (Fig. 3) is clearly decreasing with increasing atomic number; the degree to which this is the case has relevance for estimates of the mass of the supernovae that originally produced these elements. The present result suggests a decrease in the slope δ[X/H] / δ[Fe/H] by about a factor of two when X changes from O to Ca, but observations of more stars are necessary before this number can be adopted and applied in further studies.

The general overabundance of light elements is of importance for stellar evolution calculations, since these elements provide a dominating fraction of the total opacity throughout most of the stellar models. Thus, the Z variable should not be uncritically identified with an overall metal abundance, determined from spectroscopic or photometric measures of, predominantly, spectral lines of the iron-peak elements. It is not yet known whether the modifications resulting when these non-solar abundance ratios are included in stellar evolution studies are vital for evolutionary tracks and estimates of stellar ages.

The two "odd" (by atomic number) elements Na and Al show a less marked overabundance, if any, for the metal-poor disk stars (Fig. 3). Since Mg, in contrast to Fe, is thought to be produced in the same astrophysical regions as Na and Al, we have plotted [Na/Mg] and [Al/Mg] versus [Mg/H] in Fig. 4. Obviously, the more metal-poor stars show a more negative [Na/Mg] value and, probably, also a significantly negative [Al/Mg] value. This odd-even effect was predicted by Arnett (1971) and Truran and Arnett (1971) from calculations of explosive carbon burning, and the effect was expected to be the result of explosions in matter with a small neutron excess, such as in Pop II stars. Here, we have traced the effect also for disk population stars. Explosive nucleosynthesis in metal-rich environments should yield smaller odd-even effects, since in these stars the CNO burning has increased the ^{14}N abundance, which controls the neutron excess. Woosley and Weaver (1982 a, b) have calculated the outcome of explosive C and Ne burning for model Pop I and Pop II supernovae, with solar abundances of heavy elements, and one hundredth

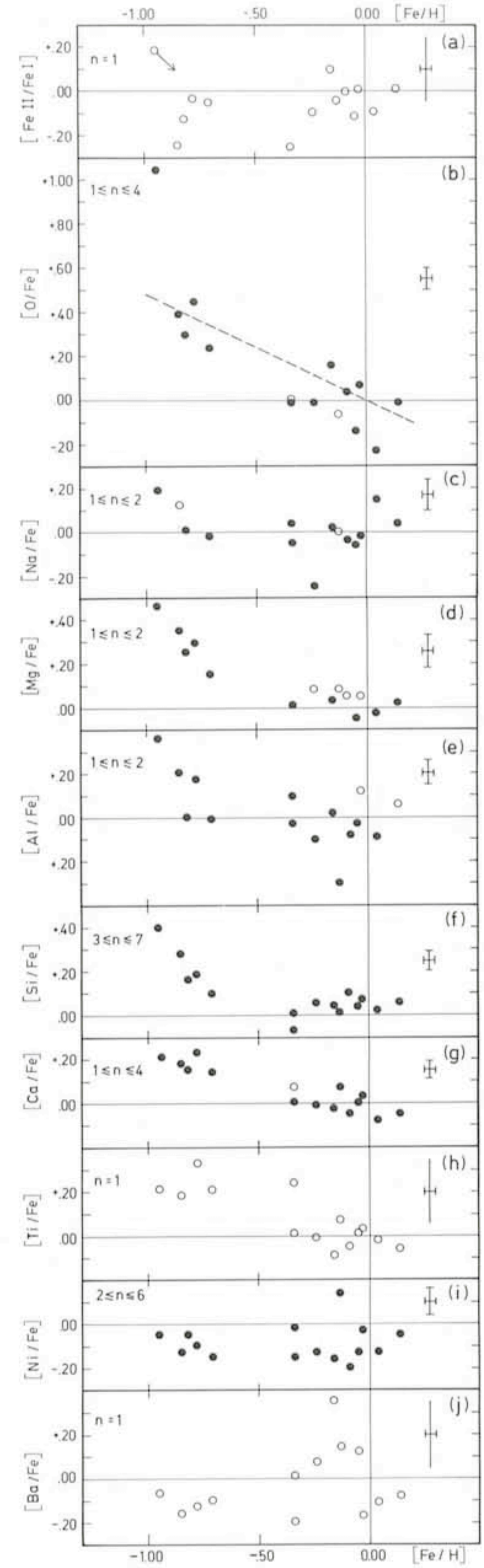

Fig. 3: *Logarithmic abundances relative to the Sun, [X/Fe] = log $(N_X/N_{Fe})_*$ − $\log(N_X/N_{Fe})_\odot$, plotted against [Fe/H] in (b)–(j). "n" indicates the number of lines used in each determination. The error bars indicate the mean for all stars of the standard deviations of [X/Fe] and [Fe/H], respectively. Open circles denote stars with n = 1, for which the vertical error bars are not defined. (a) The upper panel displays the ionization balance of iron. If [Fe II/Fe I] is systematically different from zero this may indicate errors in the fundamental parameters, e.g. the adopted surface gravity, or in the assumption of LTE as discussed in the text. In (b) the dashed line is the relation found for F dwarfs by Clegg et al. (1981).*

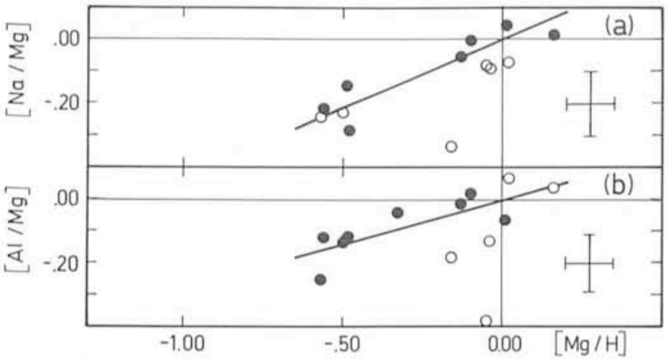

Fig. 4: *(a) Abundance ratio [Na/Mg] as a function of magnesium abundance. The error bar is calculated as in Fig. 3. Open circles denote stars where only one line of either Na or Mg was measured and for which the error bar is not defined. The line is a least squares fit to the points, required to pass through the origin. The points denoted by filled circles were given a weight of two, and those denoted by open circles a weight of one. The slope of the line is [Na/Mg] = (0.43 ± 0.08) · [Mg/H]. (b) [Al/Mg] as a function of [Mg/H]. The symbols are defined in analogy with (a). The slope of the least squares fit is [Al/Mg] = (0.28 ± 0.10) · [Mg/H]. The two panels support the prediction of Arnett (1971) and Truran and Arnett (1971) that elements with odd numbers of nucleons were less abundantly produced relative to even-numbered nuclei in metal-poor stars with low neutron excesses.*

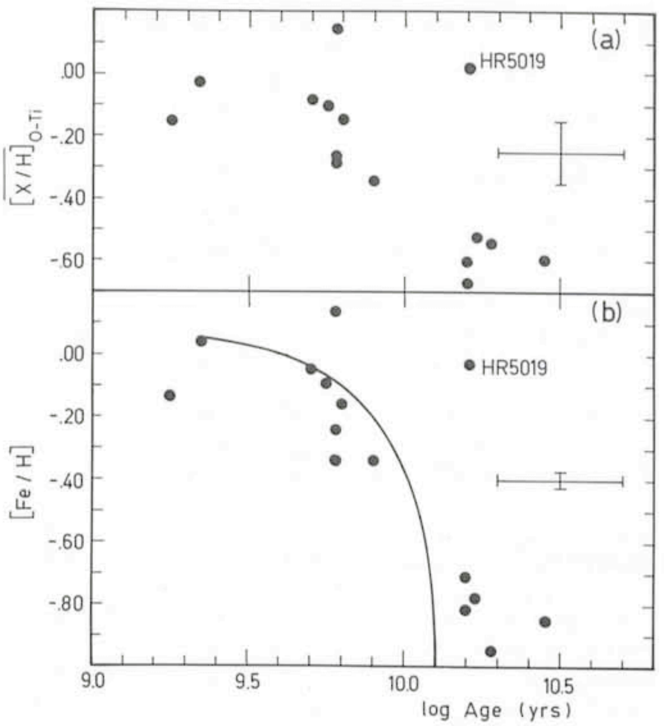

Fig. 5: *Abundances as a function of stellar age, (a) mean value of [X/H] for the "light" elements, X = O, Na, Mg, Al, Si, Ca and Ti; (b) [Fe/H] as a function of age. The curve indicates the time variation of the metal abundance in the solar neighbourhood as derived by Twarog (1980), from uvbyβ photometry of F dwarfs. The position of the star HR 5019 is also indicated.*

thereof, respectively. The slopes in Fig. 4 agree well with these calculations, if we interpolate to intermediate chemical compositions.

The heavy elements represented in the present study, Ni and Ba, seem to follow the iron abundance, with barium, determined from only one Ba II line, showing a relatively large scatter.

In Fig. 3 and 4 the origin denotes the position of the Sun. In all the diagrams it occupies a typical position for stars of similar iron abundances, indicating that the Sun is a typical star as regards its abundance pattern.

The present data are still too meagre to provide a firm basis for studying the build-up of the chemical elements as a function of age in the Galaxy. However, we have tentatively determined ages of the programme stars from the isochrones of Hejlesen (1980). The ages determined from the effective-temperature–luminosity diagrams (using the stellar trigonometric parallaxes for estimating the luminosity) are consistent within 0.2 dex with those obtained from the T_{eff} – log g diagrams (with log g determined photometrically from δc_1). The latter procedure was adopted here. We adopted a value of 2.0 pressure scale-heights for the mixing length, and a value of the hydrogen abundance by mass of X=0.70. The choice of these parameters is not important for the discussion here. We note, however, that a mixing length of 1.5 scale heights should shift the stars to lower ages by typically 0.1 dex. Such a shift would improve the agreement between the Hejlesen solar model and the Sun. The abundances of the lighter elements and the iron-peak elements are plotted as a function of stellar age in Fig. 5a. It is seen that for the present sample of stars the abundances of lighter elements, as well as that of iron and nickel can be represented by monotonic functions decreasing with stellar age. The most noteworthy exception from this is the star HR 5019 (61 Vir). Although this star has a high metal abundance, it is found to be $1.6 \cdot 10^{10}$ years old, both with the photometric method (with δc_1, as a gravity criterion) and the parallax method. It also has a relatively high space velocity, 62 km/s, for being so metal rich. However, this star is significantly cooler than the rest of our stars, and possible systematic errors in the age determinations may affect this star differently as compared with the hotter stars. The star may be worth a closer investigation. The general variation of [Fe/H] with age appears rather consistent with results derived earlier by Twarog (1980) on the basis of uvbyβ photometry for many F dwarfs, see Fig. 5b, in view of the fact that the isochrones used by Twarog were calculated with an assumed mixing length of 1.0 scale heights. When a considerable fraction of the planned sample of stars in the present investigation have been analysed, further conclusions will be possible as regards the age variation of abundances, the uniformity of abundances at any given age in the Galaxy, as well as possible tendencies for star formation to occur in bursts.

ESO Workshop on the Production and Distribution of Carbon, Nitrogen and Oxygen in Stellar Systems

A 3-day workshop to discuss observational and theoretical aspects concerning the presence of carbon, nitrogen and oxygen in stars, clusters and galaxies, will be held at ESO, Garching, 13–15 May, 1985. Contact I. J. Danziger, ESO, for more information.

Acknowledgements

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The RPCS Detector

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A one-dimensional dual array linear photon counting device for optical spectroscopy of faint astronomical objects has been developed and tested.

1. Technical Description

The RPCS (**R**eticon **P**hoton **C**ounting **S**ystem) is based on the principles given in its original form by Shectman and Hiltner (1) and utilizes a self-scanning RETICON dual photodiode array model CP 1008 (2 x 936 pixels, each 30 μ x 375 μ). One array is used for the "object", the other for the "sky".

The light amplification system consists of a 3-stage magnetic focused EMI image tube with a UV zinc crown entrance window and a standard S20 photo-cathode followed by a 3-stage electrostatic focused VARO image tube. The output from the EMI tube is optically coupled to the entrance of the VARO tube by an 85 mm f/1 Repro-Nikkor lense.

The light output from the VARO tube is transferred to the diode array through a short fiber-optic.

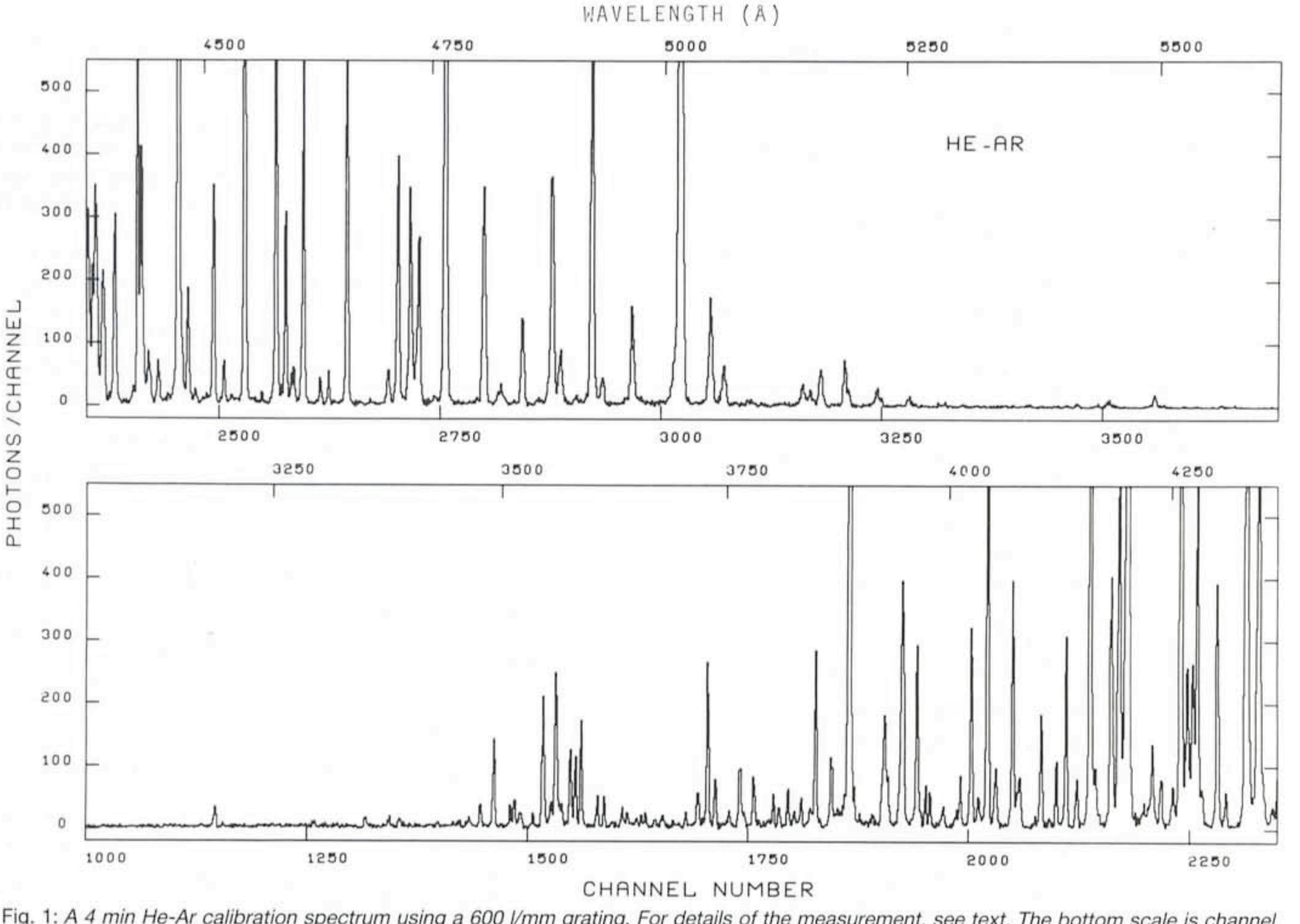

Fig. 1: *A 4 min He-Ar calibration spectrum using a 600 l/mm grating. For details of the measurement, see text. The bottom scale is channel numbers, and each channel is shown. The top scale is the corresponding wavelengths in Å and has been determined by fitting a 3' order polynomial. The ordinate is observed number of photons per channel.*