7. STELLAR ABUNDANCES

REVIEW OF ABUNDANCES FOR MID-TEFF RANGE STARS

P.E. NISSEN
Institute of Physics and Astronomy
University of Aarhus, DK-8000 Aarhus C, Denmark

1. Introduction

Among the mid-$T_{\rm eff}$ (5000 - 7000 K) range stars, those on or near the main sequence are particularly important, because they provide much information on Galactic evolution and nucleosynthesis of the elements. This is due to the fact that these stars represent an age range from 0 to 15 Gyr, and a metallicity range from $[Fe/H] \simeq -4.0$ to $+0.3$. Furthermore, it is likely that the present composition of elements in their atmospheres is similar to the composition of the interstellar gas from which they were formed, and that the present kinematics of the stars give information about their birthplaces. Hence, by observing selected samples of nearby F and G main sequence and subgiant stars one has the possibility to study the chemical and dynamical history of our Galaxy. Due to space limitation the present review is limited to these F and G stars. Supergiants are not discussed, but it should be emphasized, that their abundances are important for studies of advanced stellar evolutionary phases and determinations of the chemical composition of nearby galaxies. e.g. the Magellanic Clouds (Hill et al. 1995).

Important problems in connection with studies of the element abundances in F and G stars are: *i*) Li, Be and B abundances vs. [Fe/H] and $T_{\rm eff}$ in order to gain insight into the complex problems of stellar depletion and cosmic ray production of these elements with the ultimate goal of determining an accurate value of the primordial abundance of ^{7}Li. This problem has gained new interest with the possible detection of deuterium in distant quasar absorption systems at a level of $D/H \simeq 2 \times 10^{-4}$ (Songaila et al. 1994), which requires a ^{7}Li abundance of $Li/H \simeq 2 \times 10^{-10}$ according to standard Big Bang nucleosynthesis theory. *ii*) Oxygen and other α-element abundances as a function of [Fe/H] in order to study the production of these elements in supernovae of type II and Ia as a function of time. *iii*) Ba and Eu vs. [Fe/H] in order to study the sites and details of the s- and r-processes.

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iv) The metallicity distribution of G dwarfs, age-metallicity relations, and abundance ratios vs. kinematics in order to test Galactic evolution models. In all of these cases we need abundances of the elements to a rather high accuracy of say 25%. Similarly high accuracy is needed in connection with tests of stellar models from observations of stellar oscillation frequencies or in connection with the determination of stellar ages.

In the following, we shall try to to assess the accuracy of abundances that can be determined from high resolution spectra of F and G main sequence and subgiant stars.

2. The Sun

Element abundances in the Sun have recently been reviewed by Holweger (1996). Abundances derived from the photospheric spectrum show an impressive agreement with abundances in carbonaceous chondrites of type I, when Si is adopted as the reference element. For most elements the agreement is better than 10% showing that accurate abundances can indeed be derived from a stellar spectrum. Furthermore, the agreement strongly suggests that both the solar photosphere and the meteorites have the original elemental composition of the solar nebulae. A few deviations are, however, present. Li and perhaps Be have been depleted in the Sun, and C, N and O have probably escaped the meteorite formation by forming volatile gases like N_2 and CO. Hence, one cannot get any confirmation of the solar photospheric CNO abundances from the meteorites. This leaves us with some uncertainty, because the abundances of these elements are difficult to determine from the solar spectrum. In the case of oxygen, Lambert (1978) derived $A_O \equiv \log(n_O/n_H) + 12 = 8.92$ from the forbidden [O I] lines at 6300 and 6363 Å, and Sauval et al. (1984) derived $A_O = 8.91$ from infrared OH lines. Both analyses were based on the empirical, plane-parallel solar model of Holweger & Müller (1974) and assumed LTE. A 3D, non-LTE study of Kiselman & Nordlund (1995) of the same lines suggests, however, that the solar oxygen abundance is around 8.80. Such a change, amounting to 25% , may have quite a significant effect when oscillation frequencies of the Sun are used to test solar models, because oxygen contributes about half of the total heavy element abundance in the Sun.

The iron abundance in the solar atmosphere has been another longstanding problem. On the basis of accurate experimental oscillator strengths of Fe I lines, Blackwell et al. (1984) derived $A_{Fe} = 7.67 \pm 0.03$, about 50 % higher than the meteoritic value of $A_{Fe} = 7.51$. A number of recent works based on Fe II lines with oscillator strengths from lifetime measurements and experimental branching ratios (Holweger et al. 1990, Biemont et al. 1991, Hannaford et al. 1992) resulted, however, in a photospheric iron abundance that agrees well with the meteoritic value. Milford et al. (1994) and Holweger et al. (1995) obtained also a near-meteoritic value from Fe I lines. Blackwell et al. (1995), on the other hand, maintain the high photospheric Fe abundance, although they stress the sensitivity of the result to the photospheric model adopted, and their high value is supported by Kostik et al. (1996). The differences between these results seem to arise from a combination of errors in the gf-values and equivalent widths as well as uncertainties in the values of the microturbulence and the damping constants. In addition, small non-LTE effects and inhomogeneities in the solar atmosphere may affect the results. The lesson seems to be, that abundances in stellar atmospheres should as far as possible be derived from weak lines belonging to the major ionization stage of the element (Fe II in the case of iron for F and G stars), although it should be mentioned that the new broadening theory of Fe I lines by Anstee & O'Mara (1995) leads to the meteoritic iron abundance, when strong lines are applied (Anstee et al. 1997).

The excellent agreement between abundances of elements heavier than O in the solar atmosphere and in meteorites does not exclude that there has been a general diffusion of all heavy elements relative to hydrogen in the upper layers of the Sun. Proffitt (1994) and Bahcall & Pinsonneault (1995) have calculated that settling of heavier elements has reduced the present surface value of Z by about 10% relative to the original Z of the Sun. This result gets support from low-degree l oscillation frequencies, which do not agree with a model having the present solar atmospheric abundance, $Z = 0.018$, in the interior, but require $Z = 0.020$ (Basu et al. 1996). The effect is small, but may be larger in the older, metal-poor stars and it may also depend on the depth of the convection zone, i.e. $T_{\rm eff}$.

3. Solar-type stars

If the basic parameters of a star are similar to those of the Sun, then a highly accurate study of element abundances relative to the Sun can be carried out. One should apply the same set of theoretical model atmospheres to the star and the Sun, because errors in the models are then expected to cancel out. Furthermore, gf-values of the lines can be determined from the solar spectrum and applied to the stellar spectrum. As an example of such differential studies we briefly review recent work on abundances in the Hyades stars. Cayrel et al. (1985) determined [Fe/H] for late F and G dwarfs in the Hyades from weak iron lines with $T_{\rm eff}$ derived from Hα wing profiles to an accuracy of ±30 K. Boesgaard & Friel (1990) have continued this work for the earlier F stars with $T_{\rm eff}$ derived from colours. Altogether [Fe/H] is practically independent of $T_{\rm eff}$ in the range 5200 – 7000 K with a mean value of 0.12 and a dispersion of ±0.04 dex only.

Carbon abundances for the Hyades F dwarfs have been determined by Friel & Boesgaard (1990) from weak, high excitation C I lines. Again there is no trend with T_{eff}. The mean value of [C/H] is 0.05 with a scatter of ±0.08 dex. Finally, oxygen abundances in 25 F dwarfs have been derived by Garcia López et al. (1993) from a non-LTE analysis of the O I triplet at 7774 Å. Apart from an apparent increase of the oxygen abundances of stars with T_{eff} around 7000 K, [O/H] is nearly constant as a function of T_{eff} with a dispersion of ±0.08 dex. The mean value of [O/H] is as low as −0.08, which points to a surprisingly large O/Fe deficiency for the Hyades. As discussed by King & Hiltgen (1996) part of this apparent deficiency seems to arise from a systematic error of the oxygen triplet equivalent widths measured in the stellar spectra relative to the equivalent widths measured from the solar spectrum. From a careful analysis of the [O I] 6300 Å line in two Hyades dwarfs, King & Hiltgen determine $[\text{O/H}] = 0.15 \pm 0.10$ in good agreement with the Hyades [Fe/H] value.

We conclude that there is no sign of systematic abundance errors or different degrees of settling of heavy elements in the Hyades as a function of T_{eff}.

4. Metal-poor stars

In the case of more metal-poor stars, especially those with $[\text{Fe/H}] < -1.0$, differential abundance studies with respect to the Sun are rather uncertain. The structure of the atmospheres are quite different from that of the Sun due to the decrease of P_e and the increase of P_g, which changes the depth at which convection sets in. The ultraviolet flux is higher due to the decrease of line blocking causing a higher degree of over-ionization of many elements. Furthermore, gf-values are difficult to determine from the solar spectrum, because the weak lines in the metal-poor stars are strong in the Sun. Finally, there has recently been much debate about the T_{eff} scale for metal-poor F and G stars.

The uncertain situation is illustrated in Table 1, that lists some recent results for the bright, metal-poor star, HD 140283, based on LTE model atmosphere analyses of weak Fe lines with accurately measured equivalent widths. As seen, the T_{eff} values differ by up to 300 K and [Fe/H] by as much as 0.4 dex. T_{eff} was determined from colours except by Axer et al. (1994), who used the Balmer lines. The gravity was determined by requesting that the iron abundance derived from Fe I and Fe II lines should be the same except by Nissen et al. (1994), who adopted $\log g$ from the isochrones of Bergbusch & VandenBerg (1992). In this case there is a difference in [Fe/H] derived from Fe I and Fe II lines indicating a non-LTE problem. The true $\log g$ value of HD 140283 may be derived from the recent accurate parallax

TABLE 1. Atmospheric parameters for HD 140283. The [Fe/H] values given refer to $A_{Fe,\odot} = 7.51$

Reference	$T_{\rm eff}$	log$g$	[Fe/H]
Magain (1989)	5640 K	3.10	−2.58
Tomkin et al. (1992)	5640	3.28	−2.60
Nissen et al. (1994)	5540	3.50	−2.75 (from Fe I lines)
–	–	–	−2.56 (from Fe II lines)
Axer et al. (1994)	5814	3.27	−2.36
Ryan et al. (1996)	5750	3.40	−2.54

given by Dahn (1994), $\pi = 0.0145 \pm 0.0017$. Using the relations $g \propto M/R^2$, $L \propto R^2 T_{\rm eff}{}^4$ and adopting a mass of $M/M_\odot = 0.8 \pm 0.1$ from the 14 Gyr isochrone of Bergbusch & VandenBerg (1992), one derives log$g = 3.58 \pm 0.12$. Hence, the high gravity adopted by Nissen et al. (1994) is supported indicating that [Fe/H] derived from Fe I lines is too low due to a non-LTE (over-ionization) effect. A further problem with using the Fe I lines as the primary indicator of the iron abundance is their high sensitivity to temperature and hence to inhomogeneities in the stellar atmosphere. In the future it seems more promising to base [Fe/H] on Fe II lines using Hipparcos parallaxes to determine log$g$. Better gravities will also allow us to determine more accurate Be, B and and CNO abundances.

As seen from Table 2, recent determinations of the lithium abundance of HD 140283 also disagree, although the equivalent widths measured for the Li I line at 6708 Å are in good agreement. The Li abundance determined is very sensitive to both $T_{\rm eff}$ and the temperature gradient in the line forming region. Thus, the high value derived by Thorburn (1994) is due to the application of the ATLAS9 models of Kurucz (1993) with convective overshoot and a corresponding shallow temperature gradient. The very high Li abundance estimated by Kurucz (1995) is based on an inhomogeneous model, where Li in the cold regions is strongly over-ionized by the UV flux from the hot regions. It would be a surprise if this effect is indeed as large as postulated, because then one would also have expected to see a very large difference in the iron abundance derived from Fe I and Fe II lines, but Kurucz is certainly right in pointing out that the coupling between non-LTE effects and inhomogeneities in metal-poor stellar atmospheres should be studied in detail.

TABLE 2. Li abundances derived for HD 140283

Reference	T_{eff}	W(Li)	A_{Li}
Pilachowski et al. (1993)	5650 K	42 mÅ	2.05
Thorburn (1994)	5742	46	2.30
Norris et al. (1994)	5750	48	2.18
Kurucz (1995)	5750	45	$\simeq$ 3.0
Spite et al. (1996)	5540	46	1.96

5. Abundance ratios and stellar kinematics

Some abundance ratios can be determined more accurately than the Fe and Li abundances discussed in Sect. 4. Despite the large differences of [Fe/H] quoted in Table 1, the [Mg/Fe] ratios derived by the same authors agree within ±0.1 dex. In general, the abundance ratio between two elements with about the same ionization potential, will be rather insensitive to errors in T_{eff} and model atmospheres, if weak lines from the same ionization stage are used. Hence very accurate abundance ratios can be obtained especially when stars having similar atmospheric parameters are compared. In this way some interesting correlations between abundance ratios and stellar kinematics have recently been discovered.

Edvardsson et al. (1993) determined the ratio between the abundances of the α-elements (O, Mg, Si, Ca, and Ti) and iron in 189 disk stars as a function of [Fe/H]. In the metallicity range, $-0.8 < [\text{Fe/H}] < -0.4$, corresponding to the transition from the thick to the thin disk, [α/Fe] depends on the kinematics. Stars with large Galactic orbits, $R_{mean} > 9$ kpc, have smaller [α/Fe] values than stars with $R_{mean} < 7$ kpc. The correlation can be interpreted as due to a more rapid chemical evolution in the inner regions of the Galaxy, i.e. SNe of type Ia start to contribute iron at a lower metallicity in the outer parts than in the inner parts.

More recently, Nissen & Schuster (1997) have studied two groups of stars with $-1.3 < [\text{Fe/H}] < -0.4$. The stars were selected from the V_{rot}-[Fe/H] diagram of Schuster et al. (1993), where V_{rot} is the stellar velocity component in the direction of Galactic rotation. Stars in the first group (the halo stars) have $V_{\text{rot}} \simeq 0$ km s^{-1}, whereas stars in the second group (the disk stars) have $V_{\text{rot}} \simeq 200$ km s^{-1}. The stars are confined to rather narrow ranges in T_{eff} and gravity, $5400 < T_{\text{eff}} < 6500$ K and $4.0 < \log g < 4.6$ respectively, so that very accurate differential abundance ratios could be derived from high resolution, high S/N spectra obtained with the ESO NTT. As seen in Fig. 1, the majority of the halo stars (shown by open circles)

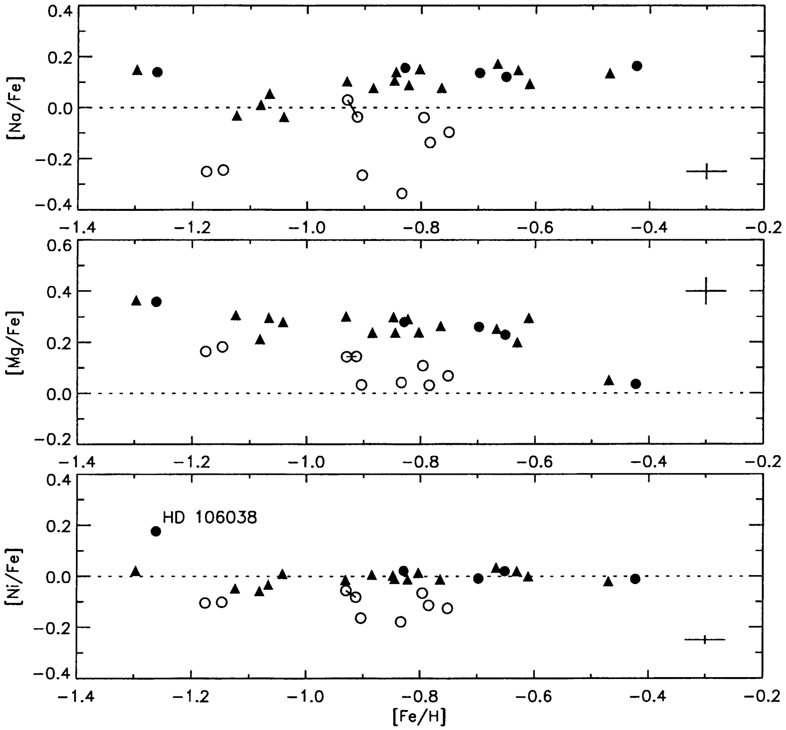

Figure 1. Na, Mg and Ni abundances relative to Fe as a function of [Fe/H]. Disk stars are shown with filled triangles and halo stars with filled or open circles. The two components of a binary star are connected with a straight line. One sigma error bars, valid for the relative abundance ratios, are shown to the right

have Na/Fe, Mg/Fe and Ni/Fe ratios that deviate very significantly from the corresponding ratios for the disk stars. Furthermore, the deficiencies in Na and Ni are strongly correlated. These deviating halo stars tend to have larger Galactic orbits than the other stars and may therefore have been accreted from dwarf galaxies with a chemical evolution history different from that of the Galactic disk and the inner halo.

6. Conclusion

For the Sun and solar-type stars with an overall metal-abundance similar to the solar value, relative abundances of the most important elements can be determined to an accuracy of about 10% with the possible exception of oxygen. For more metal-deficient stars, in particular those with [Fe/H] < -1.0, there may, however, be severe errors (up to 0.3 dex) in such important abundance ratios as Li/H, Be/H, B/H, Fe/H and O/Fe due to uncertainties in effective temperatures and gravities, non-LTE effects and inadequate atmospheric models. Other abundance ratios, e.g. Mg/Fe, can be determined more accurately and provide interesting information on nucleosynthesis and Galactic evolution, especially when compared to the kinematics of the stars.

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