CHEMICAL EVOLUTION OF THE GALAXY

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ABSTRACT

Recent observational studies of the age-metallicity and [α/Fe] – [Fe/H] relations for stars in the solar neighbourhood are reviewed. It is still debated if there exists a well defined trend of [Fe/H] with age or if [Fe/H] has a substantial scatter at a given age. Systematic differences in [α/Fe] between stellar populations have recently been discovered, but a detailed mapping of how [α/Fe] varies as a function of stellar position and kinematics remains to be carried out. Gaia has the potential to give an important contribution to the solution of these problems, and hence to contribute very significantly to the study of Galactic chemical evolution and galaxy formation in general. The requirement to the accuracy of the determination of parameters and abundances of late-type stars is, however, quite high, i.e. $\sigma(T_{\rm eff}) \simeq 100\,$K, $\sigma(M_{\rm V}) \simeq 0.2\,$mag, and σ[Fe/H] $\simeq \sigma$[α/Fe] $\simeq 0.1\,$dex.

Key words: Gaia; Stars: fundamental parameters; Stars: abundances; Stars: kinematics; Galaxy: evolution.

1. INTRODUCTION

This review will be concentrated on two problems that are central in studies of the chemical evolution of the Galaxy: i) The age-metallicity relation (AMR) in the Galactic disc and ii) the abundance of α-capture elements relative to iron, [α/Fe], as a function of metallicity, [Fe/H]. Concerning the first problem, it is still unclear if there exists a well defined AMR in the Galactic disc as advocated by e.g. Pont & Eyer (2004) or if there is only a small change in the mean metallicity of the thin disc since its formation and a large scatter in [Fe/H] at all ages as found by Nordström et al. (2004). Concerning the second problem, there is increasing evidence of a substantial scatter in [α/Fe] at a given metallicity related to the position and kinematics of the stars investigated, e.g., differences in [α/Fe] between thin and thick disc stars, and between stars belonging to the inner and outer halo, respectively. The significance of these problems in connection with theories of nucleosynthesis and the chemical evolution and formation of the Galaxy will be discussed together with the possible impact of the Gaia mission.

2. THE AGE-METALLICITY RELATION IN THE GALACTIC DISC

The study of the AMR in the Galactic disc has a long history with much controversy on whether there is a well-defined trend of [Fe/H] with age or whether [Fe/H] has a large intrinsic scatter at a given age. This is due to the difficulty of obtaining reliable ages of individual stars and to various kinds of biases in the observed samples of stars.

In a pioneering study of the AMR, Twarog (1980a) derived metallicities and ages from Strömgren photometry of nearly 1000 F dwarfs in the solar neighbourhood. He found that the metallicity increases monotonically from [Fe/H] ~ -0.60 in the oldest disc stars to about solar metallicity for the younger stars. This AMR is well explained by a classical one-zone chemical evolution model with a constant star formation rate (SFR) and an infall of metal-poor gas at a rate approximately equal to one-half of the SFR. The observed scatter in [Fe/H] at a given age, σ[Fe/H] $\sim$ 0.14 dex, corresponded well to that expected from the errors of the photometry, which suggests that the metals produced by supernovae are well mixed in the interstellar gas before star formation occurs.

As discussed by Twarog (1980b) in a paper presenting his photometric data, the derived AMR might, however, be affected by a temperature bias in the selected sample of stars. Only stars with the H_β index in the range 2.59 $< \beta <$ 2.72 were included. The lower limit of β corresponds to an effective temperature of about 5750 K. Hence, old metal-rich stars that have evolved to temperatures cooler than $\sim$5750 K were *a priori* excluded from the sample. If such stars exist, an incorrect AMR was derived by Twarog and the scatter in [Fe/H] among old stars was underestimated.

In contrast to the AMR of Twarog (1980a), Edvardsson et al. (1993) found a very significant dispersion of [Fe/H] at a given age for 189 upper main-sequence stars with 5600 K $< T_{\rm eff} <$ 7000 K. The sample was selected as the $\sim$20 brightest stars in nine metallicity bins ranging from [Fe/H] $\simeq -1.0$ to $+0.2$. Effective temperatures and absolute magnitudes were derived from Strömgren photometry, like in the study of Twarog, but [Fe/H] was determined from high resolution spectroscopy to a one-sigma precision of about $\pm$0.05 dex. Ages were determined from interpolation in the isochrones of Van-

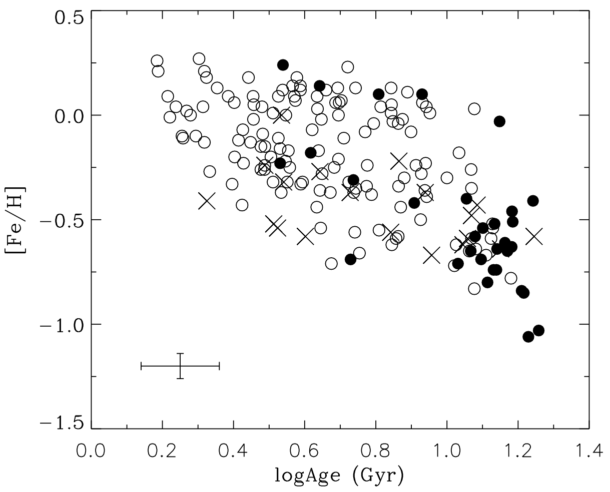

Figure 1. The AMR for the Edvardsson et al. (1993) sample of stars. Stars shown with filled circles have a mean galactocentric distance in their orbits R_m < 7 kpc. The large majority of these stars have a high probability of being thick disc stars. Open circles refer to stars with 7 kpc < R_m <9 kpc, and crosses refer to stars with R_m > 9 kpc. Typical 1-σ error bars are indicated.

denBerg (1985). The resulting AMR is shown in Figure 1. For ages between 3 and 10 Gyr, the mean value of [Fe/H] is nearly constant, but the dispersion is σ[Fe/H] $\sim$ 0.25 dex with a total range in [Fe/H] from about -0.5 to $+0.2$ dex. Although there is some correlation between [Fe/H] and the mean galactocentric distance R_m in a stellar orbit, a scatter of σ[Fe/H] $\simeq$ 0.2 dex is also present if the stars are divided according to R_m. A re-analysis of the Edvardsson et al. sample by Ng & Bertelli (1998), who used Hipparcos distances to determine absolute magnitudes and newer isochrones to derive ages, did not change the dispersion in the AMR significantly. Other spectroscopic surveys of disc stars (Chen et al. 2000; Reddy et al. 2003) have resulted in a similar large dispersion in [Fe/H] at a given age.

Recent photometric studies of large samples of F and G dwarfs with accurate Hipparcos parallaxes and ages determined from isochrones (Feltzing et al. 2001; Ibukiyama & Arimoto 2002) also suggest a flat AMR and a large scatter in [Fe/H] at all ages. Rocha-Pinto et al. (2000) have, on the other hand, obtained a steep AMR with a cosmic dispersion of 0.13 dex only, when using stellar ages derived from the chromospheric emission in the Ca II H and K lines for a sample of 552 late-type dwarfs. The study of solar-type stars in open clusters by Pace & Pasquini (2004) shows, however, that the chromospheric emission declines rapidly for ages up to ~ 2 Gyr, and then changes very little for older stars. Hence, it is surprising that Rocha-Pinto et al. (2000) could use the chromospheric emission to derive reliable ages for stars older than a few Gyrs. One may speculate that the AMR found by Rocha-Pinto et al. (2000) is an artifact of the type of calibration of the chromospheric emission index used (Rocha-Pinto & Maciel 1998). Their calibration contains a quite significant metallicity term; hence an approximately constant chromospheric emission index would lead to a pronounced metallicity trend in the ages.

In a recent work, Pont & Eyer (2004) argue that traditional determinations of stellar ages by simple interpolation between isochrones are affected by systematic biases and are more uncertain than claimed by the authors. Using a Bayesian method to take into account that a star has a higher probability of belonging to the lower main sequence than to the short-lived upper main-sequence stage, Pont & Eyer derive new ages for the Edvardsson et al. (1993) sample of stars and find a rather well-defined AMR with an intrinsic dispersion less than 0.15 dex in [Fe/H]. In particular, they question the existence of old (Age > 5 Gyr) metal-rich stars and young (Age < 6 Gyr) metal-poor stars. Recent analyses of the colour-magnitude diagram of the open cluster NGC 6791 (Stetson et al. 2003; Sandage et al. 2003) show, however, that this cluster has a metallicity in the range [Fe/H] $\simeq$ $+0.2$ to $+0.4$ and an age between 7 and 12 Gyr. Hence, old metal-rich stars do exist. The question is: how frequent are such stars and do they form a distinct population in the age-metallicity diagram?

In any case, one should be aware that the Edvardsson et al. (1993) sample is not well suited for determining the AMR in the solar neighbourhood, as also stressed by the authors. Metal-poor stars were selected from a larger volume than the solar metallicity stars, and there is a similar bias against the inclusion of old, metal-rich stars as in the work of Twarog (1980a). A much more comprehensive study of the AMR has resently been presented by Nordström et al. (2004). It is based on Strömgren photometry of a magnitude limited sample of 16 682 F, G and early K dwarf stars. The H_β and $b-y$ indices are used to derive the interstellar reddening excess and $T_{\rm eff}$. Hipparcos distances or the c_1 index serve to determine absolute magnitudes, and metallicities follow from an updated calibration of the Strömgren m_1 index. Binaries are eliminated on the basis of extensive and precise radial velocity observations. Isochrone ages are determined from the likelihood distribution of possible ages for each star taking into account the errors in the determination of $T_{\rm eff}$, $M_{\rm V}$, and [Fe/H] as well as a number of statistical biases in the sample. Furthermore, upper and lower one-sigma error limits on the age are assigned to each star.

As seen from Figure 28 in Nordström et al. (2004), the AMR diagram of a volume-limited subsample of stars within 40 pc, shows practically no change in mean metallicity from 1 to 12 Gyr but a scatter of σ[Fe/H] $\simeq$ 0.20 dex, i.e., much higher that the estimated error of 0.10 dex in the photometric determination of [Fe/H]. In retrospect, it is also noted that when a trend in mean metallicity is seen for the Edvardsson et al. (1993) sample, it is mainly because of the inclusion of a group of thick disc stars with metallicities around [Fe/H] $\simeq -0.7$ and ages in the range 10 – 14 Gyr. These thick disc stars are absent in the Nordström et al. (2004) sample of stars within 40 pc.

The survey of Nordström et al. (2004) includes space velocities, from which the mean galactocentric orbital distance, R_m, is calculated. For stars younger than about 10 Gyr, a radial metallicity gradient Δ[Fe/H]$/\Delta R_m \sim -0.09$ dex/kpc is found. According to Nordström et al., radial migration of stars in the Galactic disc has, however, no discernible effect on the dispersion of the AMR in the

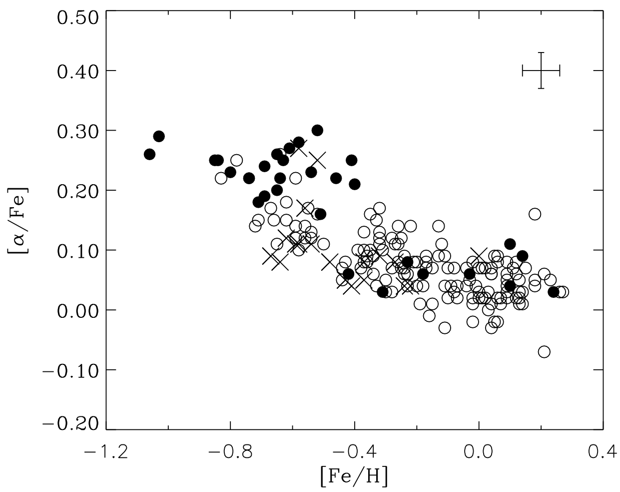

Figure 2. [α/Fe] *vs.* [Fe/H] *for the Edvardsson et al. (1993) stars. The same symbols as in Figure 1 have been used to divide the stars according to the mean galactocentric distance in their orbits.*

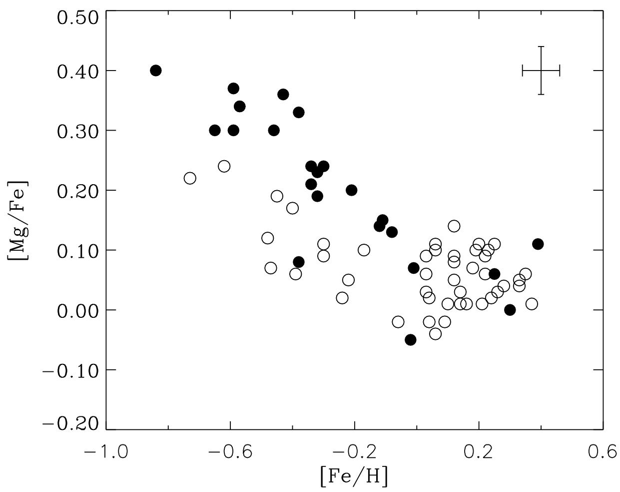

Figure 3. The Bensby et al. (2003) relation between [Mg/Fe] *and* [Fe/H] *for thick disc stars (filled circles) and thin disc stars (open circles).*

solar neighbourhood in contrast to what was suggested by Wielen et al. (1996).

A large scatter in the AMR may be explained by Galactic chemical evolution models with a high degree of inhomogeneity, e.g., self-enrichment in star-forming molecular clouds, or episodic infall of metal-poor gas triggering star formation on a time scale shorter than the characteristic mixing time in the Galactic disc. Still, it is puzzling why the mean metallicity of the Nordström et al. (2004) sample does not show any evolution with time. Interestingly, a corresponding problem is present in data relating to the distant Universe; the mean metallicity of damped Lyman-alpha systems changes little as a function of redshift and the scatter in metallicity at a given redshift is very large (Pettini 1999; Prochaska et al. 2003). Although the DLA systems probably correspond to a Galactic evolution stage that is earlier than the formation of discs, this is another piece of evidence that the rate of chemical evolution can vary enormously, e.g., according to the density of star forming regions.

From the conflicting results discussed in this section, it is evident that further observational work on the AMR is much needed. In particular, it would be important to get precise values of ages and metallicities for large samples of stars representing the main populations of the Galaxy at various distances from the Galactic center and at different heights above the Galactic plane. In order to obtain more reliable ages, an effort should also be made to improve theoretical modelling of stellar structure and evolution. As discussed in detail by Lebreton et al. (1999), there is a puzzling misfit between the theoretical ZAMS relation and the observed ZAMS for metal-poor disc stars amounting to more than 200 K in $T_{\rm eff}$. Nordström et al. (2004) encountered the same problem in connection with their age determinations and applied a metallicity dependent $T_{\rm eff}$ correction to the temperatures of the isochrones to fit the observed ZAMS relation for a given metallicity bin. Although this procedure may to a first approximation correct for the problem, it introduces additional uncertainties in the age determination, because one cannot be sure that the correction is the same for evolved stars as for unevolved stars close to the ZAMS.

3. VARIATION OF THE α/FE RATIO AMONG STELLAR POPULATIONS

3.1. Disc Stars

It is well known that the ratio between the abundances of α-capture elements (O, Mg, Si, S, Ca and Ti) and iron is enhanced by a factor of 2 to 3 relative to the solar ratio in the large majority of metal-poor halo stars, i.e., [α/Fe]= $+0.3$ to $+0.5$. This ratio agrees with the α/Fe yield ratio predicted from models of Type II supernovae (SNe). In the disc [α/Fe] decreases with increasing [Fe/H] to zero at solar metallicity, an effect that is normally explained in terms of delayed production of iron by Type Ia SNe. As the release of Type Ia elements occurs with a time delay of typically 1 Gyr, the metallicity at which [α/Fe] starts to decline depends critically on the star formation rate. Hence, [α/Fe] may be used as ‘a chemical clock’ to date the early star formation process in various parts of the Galaxy.

The Edvardsson et al. (1993) survey provided clear evidence for a scatter in [α/Fe] among disc stars with the same [Fe/H] as seen from Figure 2. [α/Fe] is defined as the average abundance of Mg, Si, Ca, and Ti with respect to Fe, and was measured with a precision of about 0.03 dex for stars having about the same metallicity. Such a high precision can be obtained when the selected stars belong to relatively narrow ranges in $T_{\rm eff}$ and gravity, like the Edvardsson et al. sample, and when the abundance ratios are derived from weak absorption lines having about the same dependence of $T_{\rm eff}$ and gravity, such as Mg I, Si I, Ca I, Ti I and Fe I lines

As seen from Figure 2, [α/Fe] for stars in the metallicity range $-0.8 <$ [Fe/H] < -0.4 is correlated with the mean galactocentric distance in the stellar orbit. Stars with $R_m > 9$ kpc tend to have lower [α/Fe] than stars with $R_m < 7$ kpc, and stars belonging to the solar circle lie in between. Assuming that R_m is a statistical measure of the distance from the Galactic center at which the star is born, Edvardsson et al. explained the [α/Fe] variations as due to a star formation rate that declines with galactocentric distance. In other words, Type Ia SNe start contributing with iron at a higher [Fe/H] in the inner parts of the Galaxy than in the outer parts.

Gratton et al. (1996) were the first to point out that the variations in [α/Fe] could also be interpreted in terms of systematic differences between the chemical composition of thin and thick disc stars. An even more clear chemical separation between thick and thin disc stars was obtained by Fuhrmann (1998). For a sample of nearby stars with 5300K $< T_{\rm eff} <$ 6600 K and 3.7 $< \log g <$ 4.6, he derived Mg abundances from Mg I lines and Fe abundances from Fe I and Fe II lines. In a [Mg/Fe] vs. [Fe/H] diagram, stars with thick disc kinematics have [Mg/Fe] $\simeq +0.4$ and [Fe/H] between -1.0 and -0.3. The thin disc stars show a well-defined sequence from [Fe/H] $\simeq -0.6$ to $+0.4$ with [Mg/Fe] decreasing from $+0.2$ to 0.0.

In a more recent work Bensby et al. (2003) selected two groups of F and G dwarf stars with high probability of belonging either to the thin or the thick disc. The thin disc stars have total space velocities with respect to the LSR, $V_{\rm tot} < +60\,{\rm km\,s^{-1}}$, whereas the thick disc stars are confined to the range 80 $\rm km\,s^{-1} < V_{\rm tot} < 180\,km\,s^{-1}$. A high resolution abundance study of these stars reveals a clear difference in the trends of [α/Fe] vs. [Fe/H] for thin and thick disc stars, respectively, as shown for [Mg/Fe] in Figure 3. Below [Fe/H] $\simeq -0.4$, [Mg/Fe] in the thick disc stars is approximately constant at a level of about 0.35 dex, and the thick disc is clearly separated from the thin disc. Above [Fe/H] $\simeq -0.4$, [Mg/Fe] in the thick disc declines and the two discs merge together. The same trends are seen for [O/Fe] (Bensby et al. 2004), [Si/Fe], [Ca/Fe] and [Ti/Fe]. Hence, Bensby et al. suggest that star formation in the thick disc went on long enough that Type Ia SNe started to enrich the gas out of which following generations of thick disc stars formed.

It is, however, questionable if the high-velocity metal-rich stars really belong to the thick disc. Mishenina et al. (2004) find the same trends as Bensby et al. (2003) for a sample of 172 stars with ELODIE high-resolution spectra (Prugniel & Soubiran 2001), but point out that the majority of the high-velocity, metal-rich stars have quite small velocities perpendicular to the galactic plane. Instead of belonging to the thick disc they may be connected to the so-called ζ Herculis branch of disc stars in the U, V plane and have originated from the inner part of the Galaxy as suggested by Nordström et al. (2004).

It should also be noted that when selecting thin and thick disc stars, Bensby et al. (2003) have avoided stars with intermediate kinematics. In a volume limited sample one may well find such 'transition' stars. As seen from Figure 2, the Edvardsson et al. (1993) sample shows a more smooth distribution of [α/Fe] in the metallicity range $-0.8 <$ [Fe/H] < -0.4 than the Bensby et al. (2003) sample in Figure 3. It may well be that the variations in [α/Fe] is caused by both a radial Galactic gradient in [α/Fe] and a systematic difference in [α/Fe] between thin and thick disc stars. Obviously, we need to determine [α/Fe] in much larger samples of stars to disentangle these abundance variations in terms of stellar kinematics and position in the Galaxy.

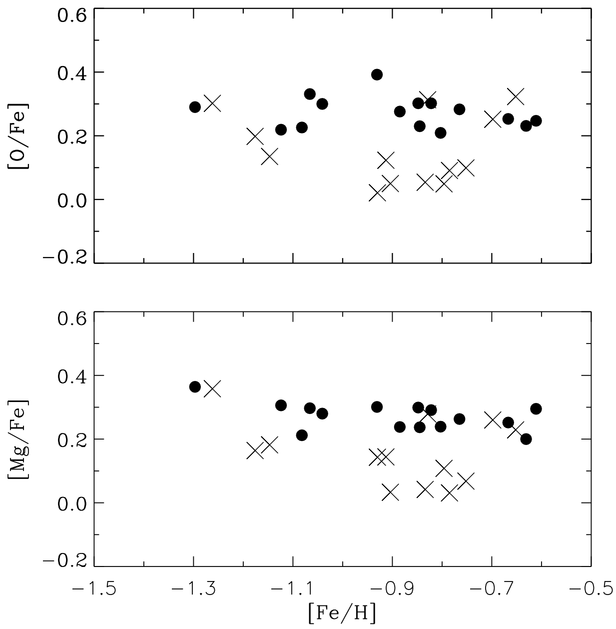

Figure 4. [O/Fe] *and* [Mg/Fe] *vs.* [Fe/H] *from Nissen & Schuster (1997). Filled circles refer to stars with a Galactic rotation velocity component* $V_{\rm rot} >$ *150 km s*$^{-1}$ *(thick disc stars), and crosses refer to stars with* $V_{\rm rot} <$ *50 km s*$^{-1}$ *(halo stars).*

3.2. Halo Stars

Photometric and spectroscopic surveys of high-velocity, main-sequence and subgiant stars in the solar neighbourhood by Nissen & Schuster (1991) and Carney et al. (1996) have shown that the metallicity range $-1.3 <$ [Fe/H] < -0.5 contains halo stars having a small velocity component in the direction of Galactic rotation, $V_{\rm rot} < 50\ {\rm km\,s^{-1}}$, in addition to thick disc stars with $V_{\rm rot} \sim 175\ {\rm km\,s^{-1}}$. Nissen & Schuster (1997) selected such two groups of stars with overlapping metallicities, and used high-resolution spectra to determine abundances of O, Na, Mg, Si, Ca, Ti, Cr, Fe, Ni, Y, and Ba. Figure 4 shows [O/Fe] and [Mg/Fe] vs. [Fe/H]. The same pattern is seen for other α-capture elements. As seen, all thick disc stars have a near-constant [α/Fe] at a level of 0.3 dex, whereas the majority of the halo stars have lower values of [α/Fe].

As discussed by Nissen & Schuster (1997), there is a tendency for the α-poor halo stars to be on larger Galactic orbits than halo stars with a high [α/Fe]. From this they suggest that halo stars with low-α abundances have been formed in the outer part of the halo or have been accreted from dwarf galaxies, for which several models, e.g., Gilmore & Wyse (1991), predict a solar α/Fe ratio

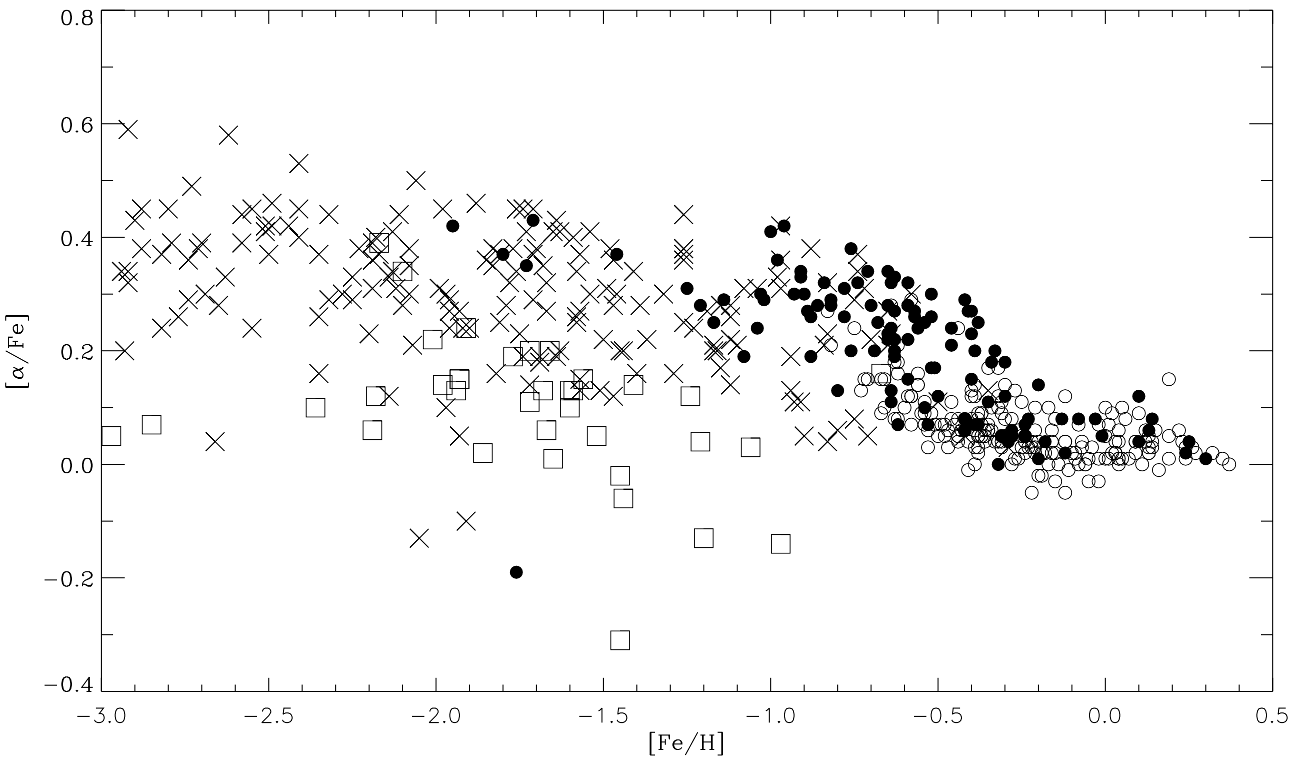

Figure 5. [α/Fe] *vs.* [Fe/H] *for stars from Table 2 of Venn et al. (2004) having a probability of at least 80% of belonging to either the thin disc (open circles), the thick disc (filled circles) or the halo population (crosses). Open squares refer to K giants in dSph galaxies*

at [Fe/H] $\simeq -1.0$ as a consequence of an early star formation burst followed by a long dormant period. Furthermore, the α-poor halo stars have low ratios of [Na/Fe] and [Ni/Fe] – an abundance anomaly shared with some K giant stars in dwarf spheroidal (dSph) galaxies (Nissen 2004).

For the more metal-poor part of the halo ([Fe/H] < -1.3) α-poor stars are quite rare in the solar neighbourhood, but they do exist. Ivans et al. (2003) have made a homogeneous abundance analysis of these stars and provide evidence that the chemical enrichment and star formation histories varied from region to region in the Galactic halo.

In a search for chemical signatures for hierarchical galaxy formation, Venn et al. (2004) have compiled recent accurate abundances and kinematics for nearly 800 stars in the solar neighbourhood. Each star is assigned probabilities for belonging to the thin disc, the thick disc and the halo population by adopting the following velocity dispersions and mean Galactic rotation velocities:

- Thin disc: (σ_U, σ_V, σ_W) = (45, 25, 20) km s^{-1}; $V_{\rm rot}$= 220 km s^{-1}
- Thick disc: (σ_U, σ_V, σ_W) = (65, 40, 40) km s^{-1}; $V_{\rm rot}$= 180 km s^{-1},
- Halo: (σ_U, σ_V, σ_W) = (140, 105, 95) km s^{-1}; $V_{\rm rot}$= 0 km s^{-1},

In Figure 5, the data in Table 2 of Venn et al. (2004) are used to plot [α/Fe] as a function of [Fe/H] for stars having a probability of at least 80% of belonging to one of the three populations. The α-element abundance is defined as the average abundance of Mg, Ca and Ti. In addition to Galactic stars, 36 K giants in dSph galaxies are also plotted using the data given in Venn et al. (2004). The sources of their abundances are Shetrone et al. (2001), Shetrone et al. (2003) and Geisler et al. (2004).

Figure 5 shows the same separation of [α/Fe] between thin and thick disc stars as discussed in Section 3.1. In addition, a significant dispersion of [α/Fe] among halo stars is apparent. As mentioned by Venn et al. (2004), there is a hint that halo stars with strong retrograde motion ($V_{\rm rot} < -200$ km s^{-1}) have a lower [α/Fe] than the rest of the halo stars. The stars in the dSph galaxies, on the other hand, have even lower values of [α/Fe]. From this and a similar offset in [Ba/Y] between halo stars and dSph galaxies, Venn et al. argue that the Galactic halo has not been assembled by continuous merging of low-mass galaxies similar to present-day dwarf spheroidals. This important conclusion, which is at variance with modern cosmological models of hierarchical structure formation, should be further tested. There could be systematic errors in the abundance determinations of the faint stars in dSph galaxies relative to Galactic stars. Furthermore, it is obvious that we need much greater surveys to map the variation of [α/Fe] as a function of stellar position and kinematics. In particular, it would be interesting to reach a large sample of stars in the outer regions of the Milky Way.

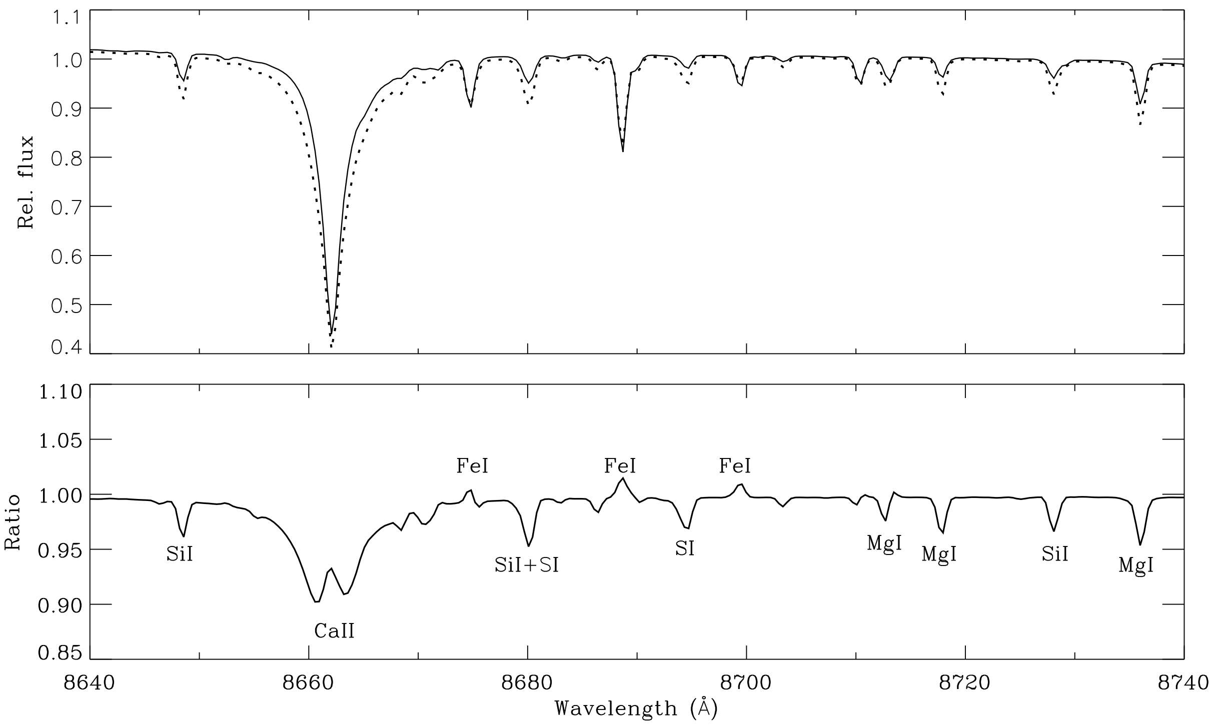

Figure 6. Synthetic spectra with the Gaia RVS resolution of $R = 11\,500$ from Zwitter et al. (2004) for a star with $T_{\rm eff} = 6000$ K, $\log g = 4.0$ and [Fe/H] $= -0.5$. In the upper part of the figure the solid line shows the spectrum for [α/Fe] $= 0.0$ and the dotted line refers to [α/Fe] $= +0.4$. The lower part of the figure shows the ratio between the [α/Fe] $= +0.4$ and the [α/Fe] $=0.0$ spectrum.

4. IMPACT OF GAIA

4.1. The AMR

Gaia may give a very significant contribution to the study of the AMR in the Galaxy, but this requires that a high accuracy of stellar parameters is obtained for stars situated in the turnoff region of the HR-diagram. $T_{\rm eff}$ should be determined to an accuracy better than 100 K, the absolute magnitude better than 0.2 mag, and [Fe/H] to an accuracy of 0.10 dex. As shown by Haywood (2005), larger errors, e.g., ±150 K in $T_{\rm eff}$ and ±0.15 dex in [Fe/H], tend to wash out interesting structures in the age-metallicity diagram, such as a well-defined AMR like the one obtained by Twarog (1980a) plus a population of old metal-rich stars.

The requirement to the accuracy of $T_{\rm eff}$ means that the error on the interstellar reddening excess should not exceed $\sigma(E(B-V)) \sim 0.02$. Alternatively, one could include a narrow (~ 5 nm) filter around the H_α line in the Gaia photometric system in order to be able to measure a reddening free H_α-index. Such an index will be quite sensitive to $T_{\rm eff}$ for turnoff stars. An error of 0.2 mag on $M_{\rm V}$ translates to a distance error of 10%, which for F and G dwarf stars corresponds to a distance of about 3 kpc according to the *Gaia Concept and Technology Study Report* (ESA 2000). This is sufficient to include the major populations of the Galaxy except the Galactic Bulge. Furthermore, it is important that Gaia will be able to separate out binary stars by detecting anomalies in the proper motions or by discovering radial velocity variations. Finally, precise abundance determinations are a must when studying the AMR, including an estimate of [α/Fe], which has a non-negligible effect on the age determination.

4.2. The α-elements

As discussed in detail by Katz et al. (2004), the Gaia Radial Velocity Spectrometer (RVS) will allow the determination of individual abundances of some elements. In the wavelength range of the RVS (848 - 874 nm) several α elements (Mg, Si, S, Ca, Ti) have absorption lines, which are measurable at the resolution of the RVS ($R = \lambda/\Delta\lambda = 11\,500$) for late-type stars. Figure 6 shows synthetic spectra in part of the RVS band for a star with $T_{\rm eff} = 6000$ K, $\log g = 4.0$, [Fe/H] $= -0.5$ and two values of [α/Fe]: 0.0 and $+0.4$. The spectra are taken from the library of Zwitter et al. (2004), who used ATLAS9 models (Kurucz 1993) to compute a large grid of spectra in the Gaia RVS band.

As seen from Figure 6 the α-element lines appear as 'absorption' lines in the ratio between the [α/Fe] $= +0.4$ and the [α/Fe] $=0.0$ spectrum. The fact that the Fe I lines show up as weak 'emission' line is due to an indirect atmospheric effect; the enhanced α-element abundance increases the electron pressure and hence the continuous opacity due to H^-. Since the line strength depends on the ratio between the line absorption coefficient and the continuous opacity, Fe I lines become weaker when the α-element abundance increases. Altogether, the signal of [α/Fe] variations in the Gaia RVS band is quite pronounced.

The Gaia RVS spectral band contains 3 Mg I, 4 Si I, 2 S I and 7 Fe I lines, which are suitable for determining the [α/Fe] ratio for late-type disc stars. Since all of the lines originate from the neutral stage of the elements, the derived ratio is fairly insensitive to errors in $T_{\rm eff}$ and gravity. For a S/N of about 50 per spectral pixel it should be possible to determine [α/Fe] with a precision of about 0.1 dex from these lines. This is not quite good enough to study [α/Fe] variations between individual stars, but with Gaia there is the possibility to group stars according to distance and kinematics and hence look for small systematic variations of [α/Fe] between stellar populations.

As estimated by Katz et al. (2004), a S/N of 50 will be obtained at the end of the Gaia mission for G and K stars of magnitude $V \simeq 13$. Hence, [α/Fe] can be studied for G dwarf stars out to about 400 pc and for K giants out to 4 kpc from the Sun. For the more metal-poor stars with [Fe/H] < -1.5, it will, however, be difficult to obtain [α/Fe], because the lines mentioned above are too faint to be measured with the resolution of the Gaia RVS. The infrared Ca II triplet could still be used as an indicator of the α-element abundance, although the rather strong dependence of these lines on $T_{\rm eff}$, gravity and chromospheric activity, make them difficult to use. One will, however, miss a measure of the iron abundance, and hence only get the Ca abundance.

Depending on the final choice of filters, Gaia may also provide a photometric estimate of [α/Fe]. This would have the advantage that fainter and more metal-poor stars could be reached, but it is an open question if sufficient accuracy can be obtained to make this an interesting option. Tautvaišienė & Edvardsson (2002) have made a preliminary discussion of the possibilities on the basis of synthetic spectra calculated by the aid of new MARCS models. The best indicators of α-element abundances are the Ca II H and K lines and the MgH band plus the Mg I b triplet in the 510 – 520 nm region. These lines are, however, quite sensitive to variations in $T_{\rm eff}$ and gravity, and the flux in the filters covering the relevant wavelength regions is affected by CN and C_2 molecular bands and hence by variations in C and N abundances. A more detailed analysis is needed to see if a clean and sensitive index of [α/Fe] can be obtained from the Gaia photometric system.

5. CONCLUSIONS

The relations between stellar age, metallicity and [α/Fe] provide very important constraints on models for the chemical evolution of the Galaxy. Attempts to determine the AMR in the solar neighbourhood have, however, given conflicting results especially regarding the intrinsic scatter of [Fe/H] at a given age and the importance of old ($\sim$ 10 Gyr) metal-rich stars. Concerning [α/Fe], recent work points to systematic differences between thin and thick disc stars, but radial Galactic gradients in [α/Fe] may also be present. In addition, there are interesting variations in [α/Fe] among halo stars, which may give information about hierarchical galaxy formation.

Much larger surveys of stellar ages, metallicities and [α/Fe] as a function of galactocentric distance and kinematics are needed to progress in these kinds of studies. Gaia has the potential for providing such a survey for late-type stars, but the requirement to the accuracy of stellar parameters is high: $\sigma(T_{\rm eff}) \simeq 100$ K, $\sigma(M_{\rm V}) \simeq 0.2$ mag, and σ[Fe/H] $\simeq \sigma$[α/Fe] $\simeq 0.1$ dex. The inclusion of an H_α index in the Gaia photometric system as a reddening-free indicator of effective temperature would be important to meet the requirement to the accuracy of $T_{\rm eff}$.

With the Gaia Spectrometer it will be possible to obtain an accuracy of σ[α/Fe] $\simeq 0.1$ dex but only for stars brighter than $V \sim 13$. It remains to be seen if one can reach fainter by including indices of α-element features in the Gaia photometric system. Furthermore, it is clear that Gaia will only deliver a useful index of the overall α-element abundance. To obtain abundances of individual elements, including s- and r-process abundances, one has still to rely on high-resolution spectroscopic surveys with large telescopes. Gaia will, however, provide distances and kinematics of stars in these surveys and hence also contribute very significantly to these more detailed studies of the nucleosynthesis of the elements in the Galaxy.

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