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Abundance structure of the Galactic disk

S. Feltzing

Lund Observatory, Box 43, SE-221 00 Lund, Sweden e-mail: sofia@astro.lu.se

Abstract. The current knowledge of the abundance structure in the Milky Way is reviewed. Special emphasis is put on recent results for stars with kinematics typical of the thin and the thick disks and how these results can, apart from studying the Milky Way, also give information about the origin of the elements. Two on-going studies are highlighted. One that presents new data for stars with kinematics typical of the Hercules stream and one for a small number of dwarf stars high above the galactic plane. These indicate that the thick disk is a homogeneous structure and that the Hercules stream perhaps is part of the metal-rich thick disk. Furthermore, new abundance determinations for Mn for stars with kinematics typical of the thin and the thick disk are presented. From these results the suggestion is that the observed trends for Mn in the Milky Way disks can be explained by metallicity dependent SN II yields. The impacts of surveys on the studies of the elemental abundance trends in the Galaxy are discussed. It is argued that when it comes to furthering our understanding of the abundance structure in the Galactic disk, future and ongoing surveys' major impact will be in the form of catalogues to select targets for high resolution spectroscopic follow-up. For a correct interpretation of the results from these follow-up studies it is important that the surveys have well understood completeness characteristics.

Key words. Stars: abundances – Stars: late type – Stars: Galaxy: abundances: Galaxy – disk: Galaxy – solar neighbourhood: Galaxy – structure

1. Introduction

The Galaxy is a large, complex entity and our current observational resources for high-resolution spectroscopy limit us to study mainly the stars that are closest to us. In the solar neighbourhood several different stellar populations overlap. These populations show different kinematic properties and it is therefore possible to, at least statistically, disentangle them (Freeman & Bland-Hawthorn 2002).

A combination of kinematic information and abundance results based on high resolution spectroscopy has proved to be a very valuable instrument to disentangle the histories and properties of these various stellar populations. Edvardsson et al. (1993) provided one of the first such studies; subsequent investigations have shown the disk system to be very complex indeed, see e.g. Mashonkina et al. (2003), Fuhrmann (2004), Bensby et al. (2004a), and Reddy et al. (2006). The important thing about all of these studies is that they adopt a differential methodology such that stars with different kinematic signatures are analysed and studied with exactly the same methods in the abundance analysis. This differential approach has been able to reveal intriguing differences between kinematically distinct groups, such as the thin and the thick disk (e.g. Mashonkina et

Send offprint requests to: S. Feltzing

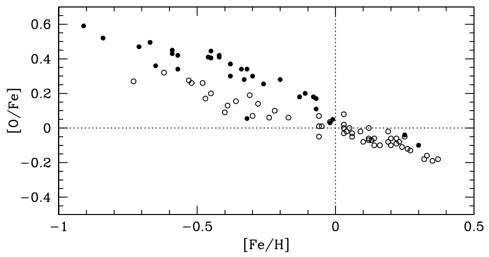

Fig. 1. [O/Fe] vs. [Fe/H] for two samples of stars. • denote stars that have kinematics typical of the thick disk whilst ∘ are stars with kinematics typical of the thin disk. Based on data from Bensby et al. (2004a) and Bensby et al. (2005).

al. 2003, Fuhrmann 2004, and Bensby et al. 2004a).

Here I will concentrate on what can be learned from studies of, mainly, dwarf stars, however, we should keep in mind that stars at other evolutionary stages also can be successfully used to study the anatomy of the Galaxy. My reasons for focusing on the dwarf stars, with spectral types close to that of the sun, is that their spectra are, reasonably, easy to analyse and, perhaps most importantly, they are the type of stars that we currently have the most extensive data sets for.

2. Abundance structure of the Galactic disk

2.1. α-elements

Fuhrmann (1998) provided what is probably the first study that directly compared, in a differential manner, the elemental abundance trends for stars with kinematics typical of the thin and the thick disk, respectively. Fuhrmann (2004) provides an update and extension of the previous work. In summary what he found is that, at a given [Fe/H], stars with kinematics typical of the thick disk are enhanced in [Mg/Fe] as compared to stars that have kinematics typical of the thin disk. This has subsequently been shown to be true for all the other so-called α-elements, including oxygen.

Oxygen is a particularly interesting element from the point of view of chemical evolution in that it is essentially made exclusively in SN II. Many elements have a combination of sources, e.g. iron is made in both SN II and Ia. These types of supernovae operate on distinctly different time scales. SN II originate in massive stars and have progenitor lifetimes from tens to one hundred million years. In contrast SN Ia are not yet fully understood apart from that they arise from binary systems (see e.g. Livio 2001). The lifetime of an object that becomes a SN Ia therefore varies between different models. For double degenerate system (i.e. made up of two white dwarfs) the lifetime might be longer than the age of the Universe. However, various recent studies have indicated the need for more than one type of progenitor system. For example, in order to explain the supernova rates in nearby galaxies Mannucci et al. (2005) suggest that both systems with a very short lifetime as well as systems with long lifetimes are needed. The effect of such combinations of SN Ia are not yet fully explored in the context of Galactic chemical evolution (however, see e.g. Scannapieco & Bildsten 2005 for a first example of such modelling).

By comparing oxygen with an element such as iron it is thus possible to deduce at what "time" the contribution from SN Ia sets in in our Galaxy. With "time" I here mean some measure of time. It could either be the age of the actual stars for which we see the signature of SN Ia or it could e.g. be the iron content of such stars. Fig. 1 shows such a plot for two kinematically selected stellar samples. In brief the two samples represent stars that have kinematics typical of either the thin or the thick disk. A full description of the method used to select the stars is given in Bensby et al. (2003) and an extended discussion of the effect of the local normalisation may be found in Bensby et al. (2005).

We see that the thick disk trend for [O/Fe] is flat at lower metallicities but at around –0.5 dex it turns downwards. A "knee" can be seen. We see no such abrupt change in the trend for the thin disk stars, but rather a gentle decline. These trends have been interpreted such that the thick disk first experiences a strong star

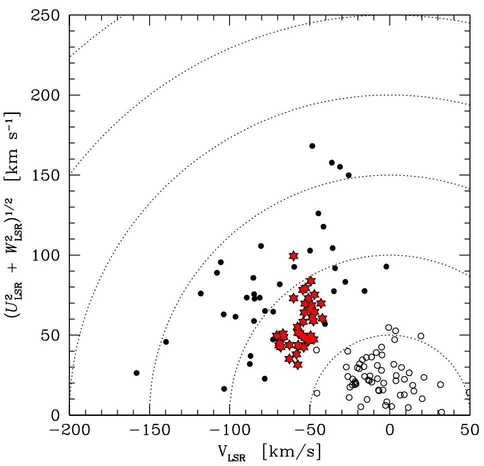

Fig. 2. Toomre diagram showing how the selected stars in the Hercules stream (★ grey/red) compares to the stars with kinematics typical of the thin (○) and thick disks (•), respectively.

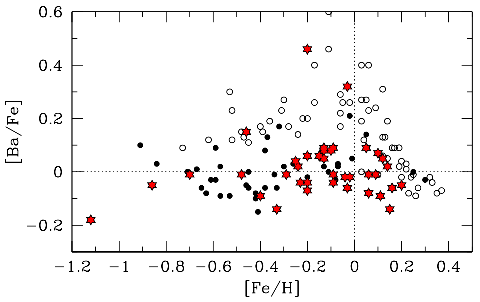

Fig. 3. [Ba/Fe] vs. [Fe/H] for stars in the Hercules stream. These stars are compared to local, kinematically selected, thin and thick disk stars (Bensby et al. 2005). ○ shows stars with kinematics typical for the thin disk, • stars with kinematics typical of the thick disk (data from Bensby et al. 2005). ★ (grey/red) indicate the stars belonging to the Hercules stream.

formation period where iron is built up, and as only SN II are operational the [O/Fe] ratio remains constant. At a given time, which depends on the time-scales involved in the SN Ia production, the iron production is increased through the contribution from SN Ia. As SN Ia do not make oxygen this results in a downward trend. The story for the thin disk is different – there the star formation rate is lower, and hence the contributions from SN II and SN Ia mix and we see no sharp features in the abundance trends that (mainly) trace these two contributions to the chemical enrichment.

2.2. Hercules stream

It has long been recognised that the disk(s) contains several streams or moving groups and Olin Eggen in particular explored these streams at an early stage. The advent of Hipparcos and its superior data sets provided a new incentive to revisit these streams again (e.g. Feltzing & Holmberg 2000). The Hercules stream provides one example of such an entity. The Hercules stream was recently identified as a dynamical structure by Famaey et al. (2005) and Navarro et al. (2004).

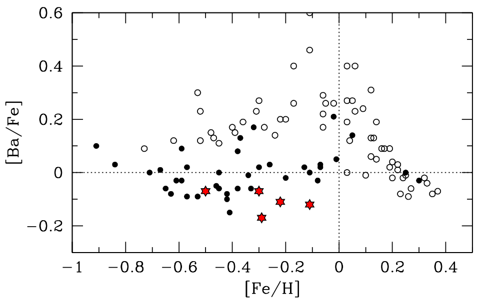

Fig. 4. Abundance plot for Ba for "in situ" dwarf stars and local thick and thin disk stars. ○ shows stars with kinematics typical for the thin disk, • stars with kinematics typical of the thick disk (data from Bensby et al. 2005). ★ (grey/red) indicate the five dwarf stars in the SGP field of Gilmore et al. (1995) that we have obtained high-resolution spectra for.

From investigations using the Nordström et al. (2004) catalogue we find that the stars in the Hercules stream appears to have a mean metallicity compatible with that of the thin disk.

However, in a recent study of the elemental abundances in Hercules stream stars (again selected purely based on their kinematic properties, see Fig.2) Bensby (2006) find that the stars show chemical signatures typical of the thick disk, see Figs. 3. This raises questions about the origin of the stream – do the stars come from the Bulge, from the inner thick disk, or are they (partly?) part of a more heated part of the thin disk? The first interpretation is less likely as we know that the stars in the Galactic bulge are more enhanced in the α-elements than the Hercules stars are at [Fe/H]=0 (Fulbright et al. 2006).

2.3. Dwarf stars at 1-2 kpc

Very few abundance studies have targeted dwarf stars well above the Galactic plane. Gilmore et al. (1995) did an extensive investigation of the metallicity distribution function at 1.5 and 2 kpc above the plane using dwarf stars as tracers of the old stellar population. They used high-resolution, low S/N spectra to derive the stellar parameters and found that there is no change in the metallicity distribution function between these two samples. In a recent study we have selected a small number of these faint dwarf stars ($V \sim 15-17$) for high-resolution spectroscopy with UVES on VLT. The first results imply that the stars show the distinct signatures of the thick disk, as observed in kinematically selected sample in e.g. Bensby et al. (2005). An example of our results are shown in Fig. 4 (Feltzing et al. in prep.).

This is not in itself surprising as the thick disk is the dominant stellar population above $\sim$ 1 kpc. However, this gives a further indication that the thick disk consists of a homogeneous stellar population pointing to a common origin for all its stars. Furthermore, this gives additional constraints on any model of Galaxy formation and evolution that sets out to explain the formation of (ubiquitous?) thick disks in spiral galaxies like our own (Yoachim & Dalcanton 2005).

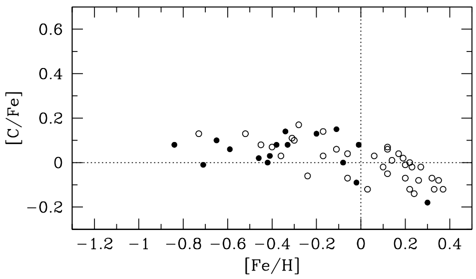

Fig. 5. [C/Fe] vs. [Fe/H] for stars in the thin (○) and thick (•) disks, respectively. Carbon abundances are from Bensby & Feltzing (2006) and iron abundances have been taken from Bensby et al. (2003) and Bensby et al. (2005).

3. Origin of elements

Here I give two examples of how studies of kinematically distinct stellar populations can help us to understand the nucleosynthetic origin of the elements. The two examples are for carbon and manganese and are taken from Bensby & Feltzing (2006) and Feltzing et al. (2006).

3.1. Carbon

Fig. 5 shows the abundance trends for carbon derived for 51 stars with typical thin or thick disk kinematics (Bensby & Feltzing 2006). Bensby & Feltzing (2006) used a forbidden carbon line for the abundance analysis and hence the results are robust against departure from local thermodynamic equilibrium. For [C/Fe] as a function of [Fe/H] the thin and the thick disk trends are fully merged. At super-solar metallicities there is an indication that the trend for the thin disk starts to drop.

Comparing with Fig. 1 we note that there is no change in the thick disk carbon trend at the [Fe/H] where the downturn in [O/Fe] happens. Although we know that carbon is not made in the same sites as oxygen it does, however, show that the source(s) that produce carbon are operating on the same time-scales as those providing the iron, i.e. the SNIa.

This, in principle, means that if we know where carbon is made we should be able to get an independent estimate of the time-scales involved in the SNIa production. However, the formation of carbon is not yet well understood, with the yields varying considerably between different studies and objects (see e.g. Gustafsson et al. 1999, Bensby & Feltzing 2006, and Carigi et al. 2005 for further discussions of this). Also, the final interpretation of the abundance trend present in the thick disk should be combined with results for the halo. However, for the halo stars one needs to rely on permitted carbon lines. As these are subject to departures from local thermodynamic modelling, detailed modelling is required (see Fabbian et al. 2006).

3.2. Manganese

Feltzing et al. (2006) have analysed four Mn I lines in 95 dwarf stars previously studied by Bensby et al. (2003) and Bensby et al. (2005). The stars were selected to have kinematics typical of the thick or the thin disk. Using these two well defined and well studied stellar samples we find that the abundance trends in the two samples differ such that the stars with thin disk kinematics are enhanced in manganese relative to stars with thick disk kinematics.

We also find that the previously reported "step" in the [Mn/Fe] vs [Fe/H] trend for disk stars in the Galaxy (McWilliam et al. 2003 and Nissen et al. 2000) is in fact due to incomplete sampling of, in particular, the more metal-rich part of the thick disk (compare the discussion in Bensby et al. 2003 of the kinematic selection of the samples of stars studied in Nissen et al. 2000 and Chen et al. 2000). Thus there is no longer any need to invoke a large spread in the age-metallicity relation for the thin disk to explain the step.

Furthermore, when comparing the manganese abundances with iron abundances the thick disk stars show a steadily increasing trend of [Mn/Fe] vs. [Fe/H] whilst the stars with kinematics typical for the thin disk show a flat trend up and until [Fe/H] = 0 and after that an increasing trend.

In order to further study the origin of manganese we have combined the new manganese abundances with oxygen abundances. Iron is made both in SN II and in SN Ia. By using oxygen, which is only made in SN II, as the reference element we simplify the interpretation of the abundance data. For the stars in Feltzing et al. (2006) we took the oxygen abundances from Bensby et al. (2004a) and added manganese and oxygen data from a number of other studies of (mainly) giant stars in the disks and halo of the Galaxy. The full data set is shown in Fig. 6.

For the halo and metal-poor thick disk, $[O/H] \leq -0.5$, the [Mn/O] trend is flat. This indicates that the production of Mn and O are well balanced. Moreover, we know from the study of Bensby et al. (2004) that the archetypal signature of SN Ias in the thick disk does not occur until [O/H] = 0. Hence the up-going trend we see after $[O/H] \simeq -0.5$ must be interpreted as being due to metallicity dependent yields in SN II. The rising trend seen for the thin disk sample could also be interpreted in this fashion, although here we do know that SN Ia contribute to the chemical enrichment and hence the increase might also be due to these objects. This is, essentially, in agreement with the conclusions in McWilliam et al. (2003).

4. Impact of surveys

The impact of future and on-going surveys on our understanding of the abundance structure of the Galactic disk are two-fold: a) for surveys that include enough spectral coverage gross abundance trends for the different populations will be derived; b) to provide catalogues from which to select samples for high-resolution spectroscopy. With regards to the abundance structure of the Galactic disk it is the latter property that will be the most important.

One of the most exiting features of the big surveys is that we will be able to identify suitable targets at large distances for differential abundance studies with the local, ongoing studies providing the reference. With large, well defined samples of such far away dwarf stars we will be able to grasp the abundance structure of the Galactic disk in a way that is not possible at the moment being, as we

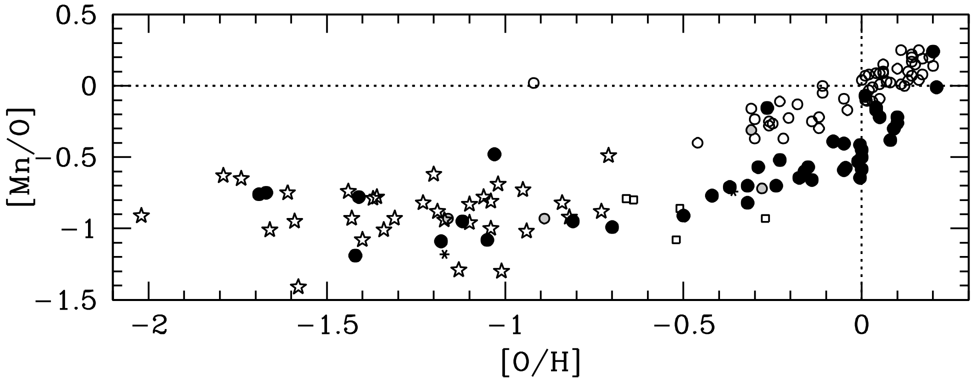

Fig. 6. [Mn/O] vs [O/H] for the Galaxy. Here we distinguish the different kinematic components instead of distinguishing the different studies. ○ indicates stars with kinematics typical for the thin disk, • indicate stars with kinematics typical of the thick disk, grey circles indicate transition objects between the thin and thick disk, ⋆ indicates stars with kinematics typical of the halo, and ∗ transition objects between the thick disk and the halo. □ shows the five stars with oxygen abundances from Meléndez et al. (2006). No kinematic information is available for these stars. Figure taken from Feltzing et al. (2006)

are, bound to the solar neighbourhood and the kinematically defined samples.

What do we need from the surveys? What we need from the surveys in order to select targets for high resolution spectroscopy is fairly straightforward and include:

1. photometry and/or low resolution spectroscopy
2. distances, parallaxes, or evolutionary stage
3. radial velocities
4. understanding of completeness

The first item on the list will provide effective temperatures and (at least for certain photometric systems as well as for low resolution spectroscopy) estimates of the metallicities of the stars. The second item is important for the derivation of surface gravity. Such information is vital for the derivation of the final elemental abundances. Often it is assumed that this property may be derived directly from the measured equivalent widths by demanding that lines arising from e.g. neutral and singly ionised iron give that same iron abundance. However, this is not necessarily true for all evolutionary stages and/or temperatures (Thévenin & Idiart 1999). Hence an independent estimate of this parameter is essential. The third item, together, with distances, give kinematic information.

The last item on the list is perhaps the most important when it come to the interpretation of the abundance trends. Some studies, notably Allende Prieto et al. (2004), have provided abundances for a volume complete sample. However, these important studies also show the current limitations in this approach: stars belonging to populations that have a low density in the solar neighbourhood, e.g. the thick disk, have a very small presence in the samples and hence any furthering of the understanding of the thick disk (for example) is limited. This is also true for other small populations, such as the streams.

Everything directly from spectra? Would it not be desirable to directly get all the information discussed above directly from the stellar spectra themselves? Indeed it would. However, the problem with ionisational equilibrium discussed above will naturally limit any such effort to narrow ranges of stellar parameters for which ionisation equilibrium may be safely assumed (see e.g. Kraft & Ivans 2003 and Bensby et al. 2003 for two examples of such parameter spaces).

Ages Determination of ages for individual stars is notoriously difficult (Jørgensen & Lindegren 2005) and using stellar isochrones it is essentially only those stars which are just leaving the main-sequence that can be age dated with any accuracy. Other methods, such as measurements of chromospheric activity, may be used to date the younger dwarf stars. So far, all studies that have looked at ages for stars typical of the thin and the thick disk agree that the thick disk is on average older than the thin disk (e.g. Fuhrmann 2004, Bensby et al. 2004b, Gratton et al. 2000). The debate about whether there is a gap in ages between these two population is still an open question – one that should be possible to resolve with larger samples of stars for which we have good ages. Such studies will also explore the age structure further away from the sun than has hitherto been feasible (e.g. Nordström et al. 2004).

Also in studies of ages for different populations it is useful to take a differential approach which means that the exact ages derived do not matter as much and that the focus can be put on finding the differences between populations, i.e. which came first and whether there are overlaps in ages between the populations. Also here the surveys should be able to provide us with samples reaching further away, exploring the structure of the Galactic disk(s).

5. Conclusions

Today we know that, in the disk of the Galaxy, stars with distinct kinematical signatures show distinctly different elemental abundance trends. These findings have implications for models of galaxy formation and evolution (both dynamical and chemical). However, so far we have only been able to scratch on the surface of the abundance structure of the Galaxy since we have been forced to mainly study the solar neighbourhood. Surveys may provide us with well defined samples of stars at large distances for which we may obtain stellar spectra and hence compare their chemical composition with that of our nearby neighbours. For success two things are essential. The first is that the stars selected for these new studies have the same overall properties as the stars we are studying in the local solar neighbourhood. This will enable so-called differential abundance studies. Such studies have proved to be very powerful also in finding small differences between stellar populations, because to first order the errors made in the abundance analysis cancel. The second requirement for success is that these new samples are drawn from stellar samples for which the sample characteristics (and in particular the completeness) are well understood so that we know if we are sampling the very rare parts of the Galaxy or major portions of its stellar populations.

Ongoing studies are starting to explore stellar populations that are not necessarily belonging to either the thick or the thin disk. For example a study of the Hercules stream shows it to have elemental abundance trends like the thick disk but a mean metallicity more like that of the thin disk.

As recently stressed by Fabbian et al. (2006) an increased knowledge of atomic data, three-dimensional model atmospheres and abundance calculations taking departures from local thermodynamic equilibrium into account are also necessary ingredients if we want to understand the formation and evolution of the stellar populations in the Galaxy. Hence, large surveys combined with detailed studies of smaller, representative samples and improved techniques of analysis are all equally essential ingredients for future progress.

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