Elemental abundance trends in the metal-rich thin and thick disks

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Thick disks are common in spiral and S0 galaxies and seem to be an inherent part of galaxy formation and evolution. Our own Milky Way is host to an old thick disk. The stars associated with this disk are enhanced in the α-elements as compared to similar stars present in the thin disk. The Milky Way thin disk also appears to be younger than the thick disk. Elemental abundance trends in stellar samples associated with the thin and the thick disks in the Milky Way are reviewed. Special attention is paid to how such samples are selected. Our current understanding of the elemental abundances and ages in the Milky Way thick and thin disks are summarised and discussed. The need for differential studies is stressed. Finally, formation scenarios for the thick disk are briefly discussed in the light of the current observational picture.

1. Introduction

Thick disks appear to be ubiquitous in spiral and S0 galaxies (e.g. Schwarzkopf & Dettmar 2000; Dalcanton & Bernstein 2002; Davidge 2005; Mould 2005; Elmegreen & Elmegreen 2006) and the Milky Way is no different as it hosts a thick disk in addition to the thin disk (Gilmore & Reid 1983). The Milky Way thick disk has a scale-height of about 1 kpc, which is three times that of the thin disk.

Available instrumentation and telescopes limits us to study the most nearby stars if we wish to derive their elemental abundances and study the chemical history of the Milky Way. Several stellar populations overlap in the solar neighbourhood. The major components are the thin and thick disks and the halo. There are also a multitude of streams and so called moving groups. The thick disk lags behind the local standard of rest by \( \sim 46 \text{ km s}^{-1} \) and the different disks have different velocity dispersions. Using kinematic information we are thus able to distinguish the thin and the thick disk stars from each other (at least on a statistical basis).

It has proved very fruitful to combine kinematical and chemical information for stars to derive the history of the disks in the Milky Way. Edvardsson et al. (1993) provided one of the very first studies to fully exploit this technique. Subsequent studies, utilising the combination of kinematic and elemental abundance information, have shown e.g. that all thick disk stars that have been studied to date are older than the thin disk stars (e.g. Bensby et al. 2003; Fuhrmann 2004). It is also now well established that stars, in the solar neighbourhood, with kinematics typical of the thick disk are, at a given \([\text{Fe/H}]\), enhanced in α-elements as compared to the thin disk stars (e.g. Bensby et al. 2004; Fuhrmann 2004, and Fig1).

2. How to define a thick disk star – selecting stars for spectroscopy

Stars in the thick disk rotate more slowly, in the plane, around the galactic centre than the thin disk stars. The thick disk stars also move higher above the galactic plane than the thin disk stars. The velocity dispersions in all three galactic velocities for the thick disk are also larger than the equivalent dispersions for the thin disk.

In the solar neighbourhood we see a mixture of stars from both disks and from the
In very rough numbers we find that ten out of a hundred stars are thick disk stars and the rest are thin disk and that one out of a thousand solar neighbourhood stars are halo stars (Buser 2000). If we want to study the elemental abundances in stars that we believe belong to the thick disk we need to decide how to select appropriate targets. There are essentially two ways to do that: **Position** – sufficiently high above the plane that the star is more likely a thick disk than a thin disk star, or, **Kinematics** – various kinematic criteria may be formulated to distinguish the disks from one another.

Different kinematic criteria have been used by different authors. The following three examples highlight some of the differences and similarities. It is interesting to note, however, that the resulting abundance trends essentially show the same results.

**Bensby et al. 2003 & 2005** All their stars are from the Hipparcos Catalogue and have radial velocities as well as Strömgren photometry available in the literature. For these stars a kinematic selection was done in the following way: assume the velocity components have Gaussian distributions unique to each population (i.e. halo, thick disk, thin disk); allow for the different asymmetric drifts; calculate the probability that each star belongs to the halo, thick disk, and thin disk, respectively; for thick disk component they selected stars that were more likely to be thick disk than thin disk, and vice versa for the thin disk. It turns out that the selection is not very sensitive to the local normalisations of the number densities for the disks (Bensby et al. 2005). This also shows, as can be expected from the procedure itself, that two fairly extreme samples are selected.

**Gratton et al. 2003** Using accurate parallaxes from the Hipparcos catalogue and radial velocities from the literature were used to calculate the orbital parameters and space velocities for the stars. The stars were then subdivided into three categories: An inner rotating population; a second population containing non-rotating and rotating stars; the third category finally contains the thin disk. This last category is confined to the galactic plane as defined by the orbital parameters of the stars (i.e. maximum height reached above the plane and eccentricity). The second category is identified as the halo and the first includes part of what is in the two other studies called halo and all of their thick disk. This population is referred to as the dissipative component as they are not able, in their kinematic as well as abundance data, to find any discontinuity between what is generally called the halo and the thick disk.

**Reddy et al. 2003 & 2006** All stars are from the Hipparcos Catalogue and have radial velocities available in the literature. A cut for distances, at 150 pc, was imposed to avoid problems with reddening. An initial selection of stars belonging to the thin and thick disks, respectively, is done by imposing cuts in $V_{\text{LSR}}$ and $W_{\text{LSR}}$. These selections are also “verified” by computing probabilities akin to those in e.g. Bensby et al. (2003).

These studies also impose criteria such that only stars within a fairly narrow range of effective temperature and $\log g$ are selected. Hence, it become possible to 1) do a differential study and 2) obtain ages for the stars based on their position in the HR-diagram.

Additionally, Klaus Fuhrmann has in a series of papers (Fuhrmann 1998; 2000 unpublished; and 2004) investigated a sample containing all mid-F to early K dwarf stars within 25 pc and with $M_V = 6$ and north of declination $\delta = 15^\circ$. As such a sample is mainly made up of thin disk stars he has added stars at larger distances that are assumed representative of the thick disk and halo. However, the basic criteria to assign a star to either thin or thick disk have evolved between the papers. In the first paper the chemical signatures (i.e. Mg abundances) were the major criteria whilst in the second paper age is envisioned as the criterion that will distinguish a star as either thin or thick disk. It also turns out that these assignments do agree with kinematic classifications based on e.g. $V_{\text{LSR}}$ and total velocity.
However, it appears to be a more robust and straightforward method to first identify stars according to reproducible kinematic criteria and then study their abundances and ages as we do not apriori have knowledge about what the thick disk is but want to find out.

3. The abundance trends in the thick and thin disks

Recent studies of the elemental abundance trends in the thin and thick disks include the following differential studies: Fuhrmann (1998, 2004), Chen et al. (2000), Mashonkina et al. (2003), Gratton et al. (2003), Bensby et al. (2003, 2004a, 2005), Bensby & Feltzing (2006), Feltzing et al. (2006), and Mishenina et al. (2004). These are complemented by studies that have focused on only one of the disks. The two most important studies of only thick disk stars are Prochaska et al. (2000) and Reddy et al. (2006). For the thin disk Reddy et al. (2003) and Allende Prieto et al. (2004) are of particular interest.

The main findings from these studies may be summarized as follows:

(a) at a given [Fe/H] the stars with kinematics typical of the thick disk are more enhanced in α-elements than the stars with kinematics typical of the thin disk (e.g. Bensby et al. 2003 & 2005; Fuhrmann 1998 & 2004; Gratton et al. 2003)

(b) other elements also show differences for the two disks, e.g. Ba, Al, Eu, and Mn (Mashonkina et al. 2003; Bensby et al. 2005; Feltzing et al. 2006; Feltzing 2006)

(c) the elemental abundance trends for the kinematically selected samples are tight (Bensby et al. 2004a; Reddy et al. 2006)

(d) studies that follow stars with kinematics typical of the thick disk up till solar metallicities note a downward trend in e.g. [O/Fe] as a function of [Fe/H]. This is most easily interpreted as a contribution from SN Ia to the chemical enrichment (Fig.1 and Bensby et al. 2003)

An essential part of the studies cited in the list above is that they all employ a differential method. That is, in the study both stars with kinematics typical of the thin disk as well as stars with kinematics typical of the thick disk are included. Furthermore, the stars only span a narrow range in effective temperature and log $g$. This means that, to first order, any modelling errors in the abundance determination cancel. It is important
Figure 2. [O/Fe] vs. [Fe/H] and [Fe/O] vs. [O/Fe] for all stars with thick disk kinematics in Bensby et al. (2003, 2004a & 2005). The stars have been divided according to how far they reach above the galactic plane. Stars with $Z_{\text{max}} > 500$ pc are marked by open squares and $Z_{\text{max}} \leq 500$ pc are marked by open stars. Compare also Fig. 3 which shows the $W$ velocities and estimated distances from the galactic plane for these stars as well as for the stars with kinematics typical of the thin disk from the same studies.

It is interesting and important to note that although different studies apply different kinematic selection criteria the results are robust and remain the same. This implies that the currently used criteria are selecting essentially the same stellar populations. The important fact we have learnt in the last decade is that stars that occupy the velocity space associated with the thick disk show elemental abundance trends that are distinct from the trends traced by stars with kinematics typical of the thin disk.

3.1. Vertical structures

Changes in the properties of the stellar populations as a function of height above the galactic plane are important clues to the formation of the galactic disk system. A slow, monolithic collapse would for example result in clear trends such that the mean metallicity would increase with decreasing distance from the galactic plane. If instead the thick disk was formed from an originally think disk that was later puffed up in a merger event we should see no such trends. In that case we would also expect the abundance trends in the thick disk to be the same at all heights.

Gilmore et al. (1995) studied the metallicity distribution function at 1.5 and 2 kpc above the galactic plane. They found no differences between the two distributions. Davidge (2005) and Mould (2005) also find that there is no appreciable gradient in the colours.
of the stellar populations as a function of the height above the galactic plane in nearby spiral galaxies. This is consistent with the result found for the Milky Way by Gilmore et al. (1995).

In Fig. 2 we have divided the stars with kinematics typical of the thick disk into two samples based on how far their $W_{\text{LSR}}$ velocities will take them above the galactic plane (Bensby et al. 2005). The two samples show exactly the same abundance trends. These findings appear to exclude a monolithic collapse for the formation of the thick disk and favour a puffing-up scenario. Tentative results from an abundance study of 5 dwarf stars situated above the galactic plane at $\sim 1$ kpc show that the elemental abundance trends for these stars are the same as for the local, kinematically selected thick disk stars (Feltzing et al. 2006, to be submitted to A&A). Figure 4 shows the results for Ba and Al. The [$\text{Ba/Fe}$] vs. [$\text{Fe/H}$] trend for the local, kinematically selected thick disk stars is well separated from that of the thin disk stars at [$\text{Fe/H}$]$\sim 0$. The five “in situ” dwarf stars clearly follow the local thick disk trend rather than the local thin disk trend. Also for Al we see a clear separation of the two trends and the stars at $\sim 1$ kpc show the same trend as the stars with kinematics typical of the thick disk.

3.2. How metal-rich can the thick disk be?

An interesting and unanswered question is: How metal-rich are the most metal-rich stars in the thick disk? When selecting stars with kinematics typical of the thick disk we do find stars with typical thick disk kinematics at up to [$\text{Fe/H}$]=0 and even a few stars...
Figure 4. [Al/Fe] and [Ba/Fe] vs. [Fe/H] for three stellar samples. • marks local solar neigbourhood stars with kinematics typical of the thick disk and ◦ mark stars with kinematic typical of the thin disk. Both samples are from Bensby et al. (2003 & 2005). Red/grey stars mark the five dwarf stars at the South Galactic Pole for which we have obtained spectra (Feltzing et al. in prep). The stars are on average ∼ 1 kpc away from the Sun.

above solar metallicity (e.g. Bensby et al. 2005). That such stars really belong to the thick disk has been questioned. Rather it could be argued that they belong to the tail of the velocity distribution of the thin disk (see e.g. discussion in Mishenina et al. 2004). Figure 3 shows the relevant kinematic data and estimated distance reached above the galactic plane for all stars in Bensby et al. (2003 & 2005)

However, tentative results for stars ∼ 2 kpc above the galactic disk show that a large portion of such stars also have solar metallicities (Arnadottir, Feltzing et al. in prep.). If the number of metal-rich stars is compatible with the number of expected thin disk stars at these heights remains to be confirmed. Also, when inspecting large kinematic samples (e.g. the sample collected in Bensby et al. 2004b) it is clear that stars with $|W_{LSR}| > 35$ km s$^{-1}$ (the velocity dispersion for the thick disk) are frequent also at solar metallicities. However, also here detailed modelling is needed to draw any firm conclusions. For now, we feel that it might be most productive to keep an open mind in this particular issue and investigate the metal-rich thick disk further.

4. Ages

For dwarf stars that have evolved of the main sequence it is possible, even though difficult, to derive their ages (Jørgensen & Lindegren 2005). Also for the studies of the age structure(s) in the disks it is important to do differential studies, i.e that all stellar parameters are derived in the same way and that all ages are derived using the same isochrones. In this way modelling errors will cancel (at least to first order) and we can
say with confidence which stars are the older ones and find out if there are any trends such
that e.g. more metal-rich stars are younger. It is also important to take $\alpha$-enhancement
into account as that tends to make a star younger (see e.g. Kim et al. 2002; Yi et al.
2001).

So far, in all abundance studies of the thin and the thick disk it is found that the stars
with kinematics typical of the thick disk are older than the stars with kinematics typical
of the thin disk (e.g. Fuhrmann 2004; Bensby et al. 2005). Recent studies of resolved
stellar populations in nearby spiral galaxies show that their thick disks also appear to be
all old, Davidge (2005) and Mould (2005).

If there is hiatus in the star formation such that there is an age gap between the thin
and the thick disk is debated (compare e.g. Gratton et al. 2003 and Bensby et al. 2004b
& 2005). Here exact selection criteria might play a rôle.

More comprehensive studies of the age properties of the thick disk component have
been done by Bensby et al. (2004b), Schuster et al. (2006), and Haywood (2006). In all
of these studies it is found that there appears to be an age-metallicity relation present
in the stellar population with kinematics typical of the thick disk. The change in ages
might be as large as 3–4 Gyr (Bensby et al. 2004b). Thus, it does appear that the star
formation in this stellar population has been extended over time.

5. Discussion

The two most important features of the disk that any model must be able to reproduce
is the fact that tight and different trends are observed for elemental abundances (e.g.
oxygen) for stars with kinematics typical of the thin and the thick disks, respectively, and
that there are no evidence that either the elemental abundance trends or the metallicity
distribution functions in the thick disk vary with height above the galactic plane (Bensby
et al. 2005; Gilmore et al. 1995).

Additional constraints are provided by the stellar ages. It appears that the stellar
population in the thick disk is older than that in the thin disk (e.g. Fuhrmann 2004;
Bensby et al. 2004b). Also, there is evidence for an age-metallicity relation in the thick
disk (Schuster et al. 2006; Haywood 2006; Bensby et al. 2004b).

Several scenarios for the formation of thick disks in spiral galaxies have been suggested.
A comprehensive, and still valid, summary can be found in Gilmore et al. (1989). Ear-
lier work focused on various versions of monolithic collapse. Although the observational
evidence is still somewhat meagre it does appear that the fact that to date no vertical
gradients have been observed invalidates this scenario. Recent efforts have focused on
ACDM realisations of the formation of Milky Way like galaxies (e.g. Abadi et al. 2003,
Brooks et al. 2004 & 2005). These models suggest that the thick disk in the solar neigh-
bourhood could be made up of a single accreted dwarf galaxy in which the stars had
formed prior to the merger but that other parts of the thick disk, e.g. closer to the Bulge,
would originate in other dwarf galaxies. If this is correct we should expect to see rather
different abundance patterns in different parts of the Milky Way thick disk as there is
no reason to believe that the merged galaxies would have the same potential wells and
hence produce identical abundance patterns. In general, if thick disk stars are accreted
to the Milky Way they must come (at least the ones close to the Sun) from the same
object as it would be hard to imagine how to create the tight abundance trends that
we observe in the local thick disk. Other models, e.g. Kroupa (2002), suggest that the
Milky Way has gone through phases of enhanced star formation due to close encounters
between the Milky Way and a passing satellite galaxy. The star formation rate would
not only be enhanced in these models but gas would also be stirred and exited to higher latitudes in the Milky Way, thus creating the thick disk stars “in situ”.

A widely advocated scenario is that what we today see as the thick disk originally was a thin disk that was heated by a minor merger between the Milky Way and a satellite galaxy. However, it currently appears that the thick disk is all old. This would mean that the last merger happened long ago (3–4 Gyr if we should believe the current age estimates). This in turn would not work well with the ΛCDM models. Another constraint is that the stars that make up our local thick disk must have formed in a fairly deep potential well as the mean metallicity of the thick disk is high (Wyse 1995). This in combination with the clear enhancement of the elemental abundances for the $\alpha$ elements which indicates that SN II dominated the chemical enrichment indicates that the if the thick disk stars did form in a satellite it must be large (Wyse 2006).

6. Summary

Our current knowledge about the thin and the thick disks can be summarised as follows. The summary has been divided into three categories:

**Controversial findings/claims:**
- The thick disk extends to $[\text{Fe/H}]=0$
- There is an age-metallicity relation present in the thick disk

**The following are items that are fairly well agreed upon:**
- The thick disk shows evidence for extended star formation
- No changes in abundance trends and/or metallicity distribution functions as a function of height above the galactic plane have been found (yet)

**Commonly acknowledged as well established are:**
- Abundance trends for kinematically selected samples differ
- The elemental abundance trends in the kinematically selected samples are very tight
- Stars with kinematics typical of the thick disk are enhanced in $\alpha$-elements as compared to the stars with kinematics typical of the thin disk (at a given $[\text{Fe/H}]$)
- The solar neighbourhood thick disk stars that have been studied are all old
- To date all stars with kinematics typical of the thick disk that have been studied with high resolution spectroscopy appear to be older than those with kinematics typical of the thin disk

The real challenge for models of galaxy formation is to explain the tight elemental abundance trends found for kinematically selected populations of disk stars, i.e. the thin and the thick disk. There is also a need to be able to accommodate the observed age constraints, i.e. the stars in the thick disk are older than those in the thin disk and perhaps that there is an age-metallicity relation present in the thick disk.

A wealth of information about the stars in the Milky Way disks have been collected so far. However, as the discussion above suggest we are still quite far away from our goal — to understand how the two disks formed and evolved. The current observational evidence does not even appear to be quite strong enough to distinguish between some of the major formation scenarios that have been proposed so far.

Future progress will depend on access to large surveys (see e.g. various contributions to the Joint Discussion 13 held at the IAU General Assembly in Prague 2006 [http://clavius.as.arizona.edu/vo/jd13/]) but it will also, in equal, measures depend on the quality of the data (i.e. high resolution, high signal-to-noise), and the treatment of
the data (i.e. the modelling of stellar atmospheres and line formation). This includes obtaining improved atomic data, 3D modelling of stellar atmospheres, and NLTE treatment of line formation.

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