Carnegie Observatories Astrophysics Series, Vol. 4:
Origin and Evolution of the Elements, 2004
ed. A. McWilliam and M. Rauch (Cambridge: Cambridge Univ. Press)

Thin and Thick Galactic Disks

POUL E. NISSEN
Department of Physics and Astronomy, University of Aarhus, Denmark

Abstract

Studies of elemental abundances in stars belonging to the thin and the thick disk of our Galaxy are reviewed. Edvardsson et al. (1993) found strong evidence of [α/Fe] variations among F and G main sequence stars with the same [Fe/H] and interpreted these differences as due to radial gradients in the star formation rate in the Galactic disk. Several recent studies suggest, however, that the differences are mainly due to a separation in [α/Fe] between thin and thick disk stars, indicating that these populations are discrete Galactic components, as also found from several kinematical studies. Further evidence of a chemical separation between the thick and the thin disk is obtained from studies of [Mn/Fe] and the ratio between *r*- and *s*-process elements. The interpretation of these new data in terms of formation scenarios and time scales for the disk and halo components of our Galaxy is discussed.

1.1 Introduction

A long-standing problem in studies of Galactic structure and evolution has been the possible existence of a population of stars with kinematics, ages, and chemical abundances in between the characteristic values for the halo and the disk populations. Already at the Vatican Conference on Stellar Populations (O'Connell 1958), an *intermediate Population II* was introduced as stars with a velocity component perpendicular to the Galactic plane on the order of $W \approx 30$ km s^{-1}. Using the m_1 index of F-type stars, Strömgren (1966) later defined intermediate Population II as stars having metallicities in the range $-0.8 <$ [Fe/H] < -0.4, and from a discussion of the extensive *uvby*-β photometry of Olsen (1983), he concluded that the intermediate Population II consisted of old, 10–15 Gyr stars with velocity dispersions (σ_U, σ_V, σ_W) significantly higher than those of the younger, more metal-rich disk stars (Strömgren 1987, Table 2).

In a seminal paper, Gilmore & Reid (1983) showed that the distribution of stars in the direction of the Galactic South Pole could not be fitted by a single exponential, but required at least two disk components—a *thin disk* with a scale height of 300 pc and a *thick disk* with a scale height of about 1300 pc. They furthermore identified intermediate Population II with the sum of the metal-poor end of the old thin disk and the thick disk. Following this work, it has been intensively discussed if the thin and thick disks are discrete components of our Galaxy or if there is a more continuous sequence of stellar populations connecting the Galactic halo and the thin disk. For a comprehensive review and a discussion of possible formation scenarios, the reader is referred to Majewski (1993).

Quite a strong indication of the thin and thick Galactic disks as discrete populations with respect to kinematics and age came from the detailed abundance survey of Edvardsson et al. (1993). On the basis of the large *uvby*-β catalogs of Olsen (1983, 1988), main sequence stars in the temperature range 5600 K $< T_{\rm eff} <$ 7000 K were selected and divided into 9 metallicity groups ranging from [Fe/H] ≈ -1.0 to $\sim +0.3$. In each metallicity group the ~ 20 brightest stars were observed. Hence, there is no kinematical bias in the selection of the stars. As shown by Edvardsson et al. (1993, Fig. 16b) and as first discussed by Freeman (1991), there is an abrupt increase in the W velocity dispersion of the stars when an age of 10 Gyr is passed. The same was found by Quillen & Garnett (2001), who reanalyzed the Edvardsson et al. sample using space velocities based on Hipparcos data (ESA 1997) and ages from Ng & Bertelli (1998). As seen from their Figure 2, the velocity dispersions are fairly constant for ages between 3 and 9 Gyr: $(\sigma_U, \sigma_V, \sigma_W) \simeq (35, 23, 18)$ km s^{-1}, corresponding to the thin disk, whereas for ages between 10 and 15 Gyr the dispersions are $(\sigma_U, \sigma_V, \sigma_W) \simeq (60, 50, 40)$ km s^{-1}, where the velocity dispersion $\sigma_W = 40$ km s^{-1} corresponds quite well to the scale height of the Gilmore & Reid thick disk. About the same values were obtained by Nissen (1995) on the basis of the original Edvardsson et al. (1993) data. Furthermore, he derived rotational lags with respect to the local standard of rest (LSR), $V_{\rm lag} \simeq -10$ km s^{-1} for the thin disk and $V_{\rm lag} \simeq -50$ km s^{-1} for the thick disk.

Although the Edvardsson et al. data for the kinematics of stars in the solar neighborhood belonging to the thin and thick Galactic disks refer to 189 stars only, the values derived agree quite well with other recent investigations. For example, Soubiran, Bienaymé, & Siebert (2003) derive $(\sigma_U, \sigma_V, \sigma_W) = (63 \pm 6, 39 \pm 4, 39 \pm 4)$ km s^{-1}and a rotational lag $V_{\rm lag} = -51 \pm 5$ km s^{-1}for the thick disk based on Tycho-2 proper motions (Høg et al. 2000) and ELODIE (Baranne et al. 1996) spectra for a sample of 400 stars in directions toward the Galactic North Pole.

In the following, we review recent studies of the chemical composition of Galactic disk stars. As we shall see, there is increasing evidence that the thin and thick disks overlap in metallicity in the range $-0.8 <$ [Fe/H] < -0.4 but are separated in [α/Fe], where α refers to the α-capture elements. Furthermore, recent studies suggest that the two disk components are also separated in [Mn/Fe] and [Eu/Ba], i.e. the *r*- to *s*-process ratio. Hence, the chemical studies support the interpretation of the thin and thick disks as discrete components of our galaxy formed at separated epochs and having different evolution time scales.

1.2 The α-Capture Elements

It is well known that α-capture elements like O, Mg, Si, and Ca are overabundant by a factor of 2 to 3 relative to Fe in the large majority of metal-poor halo stars, i.e [α/Fe]= +0.3 to +0.5. In the disk [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 supernovae (SNe) in the disk phase. As the release of Type Ia products 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 star formation process in the Galaxy.

1.2.1 The Edvardsson et al. Survey

The Edvardsson et al. (1993) survey provided clear evidence for a scatter in [α/Fe] among disk stars with the same [Fe/H]. This is shown in Figure 1.1, where [α/Fe] is plotted

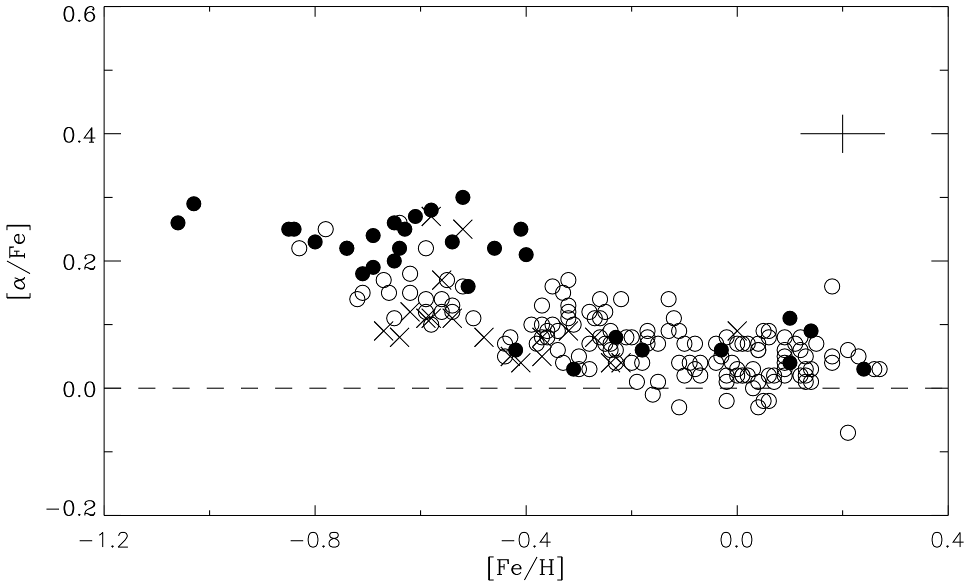

Fig. 1.1. [α/Fe] vs. [Fe/H] for the Edvardsson et al. (1993) stars. [α/Fe] is defined as $\frac{1}{4}$([Mg/Fe] + [Si/Fe] + [Ca/Fe] + [Ti/Fe]). Stars shown with filled circles have a mean galactocentric distance in their orbits $R_m < 7$ kpc. Open circles refer to stars with $7\,\mathrm{kpc} < R_m < 9$ kpc, and crosses refer to stars with $R_m > 9$ kpc. Typical 1 σ error bars, referring to differential abundances at a given [Fe/H], are indicated.

as a function of [Fe/H]. [α/Fe] is defined as the average abundance of Mg, Si, Ca, and Ti with respect to Fe, and was measured with a differential 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 the Mg I, Si I, Ca I, Ti I and Fe I lines. In other cases, like [O/Fe], where the oxygen abundance is derived from the [O I] λ6300 line, the derived abundance ratio is more sensitive to errors in atmospheric parameters and the structure of the model atmospheres (e.g. 3D effects; Nissen et al. 2002). This is why oxygen abundances were not included when calculating the average α-element abundance. It should also be emphasized that the absolute abundances and the overall trend of [α/Fe] with [Fe/H] may be affected by non-LTE effects.

As seen from Figure 1.1, [α/Fe] for stars in the metallicity range $-0.8 <$ [Fe/H] < -0.4 is correlated with the mean galactocentric distance R_m 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 was 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. As we shall see in the following, the [α/Fe] variations may, however, also be interpreted in terms of systematic differences between thin and thick disk stars.

1.2.2 Recent Studies of α-Capture Elements

Gratton et al. (1996) were the first to point out that the variations in [α/Fe] could be interpreted in terms of systematic differences between the chemical composition of thin and thick disk stars. Later, Gratton et al. (2000) studied these differences in more detail; equivalent width data from Zhao & Magain (1990), Tomkin et al. (1992), Nissen & Edvardsson (1992), and Edvardsson et al. (1993) were reanalyzed in a homogeneous way and used to derive Fe/O and Fe/Mg ratios. When the stars are plotted in a [Fe/O] vs. [O/H] diagram, two groups of disk stars with [O/H]> -0.5 appear: thin disk stars with [Fe/O]> -0.25 and thick disk stars with [Fe/O]< -0.25. The two groups show a large degree of overlap in [O/H]. Gratton et al. interpreted this as evidence for a sudden decrease in star formation rate during the transition between the thick and thin disk phases, allowing Type Ia SNe to enrich the interstellar gas with Fe without any increase in O and Mg due to the absence of Type II SNe.

An even more clear chemical separation between thick and thin disk stars has been obtained by Fuhrmann (1998, 2000). For a sample of nearby stars with $5300\,\mathrm{K} < T_{\mathrm{eff}} < 6600\,\mathrm{K}$ 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 disk kinematics have [Mg/Fe] $\simeq +0.4$ and [Fe/H] between -1.0 and -0.3. The thin disk 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. Hence, there is a clear [Mg/Fe] separation between thick and thin disk stars in the overlap region $-0.6 <$ [Fe/H] < -0.3 with only a few "transition" stars. This is even more striking in a diagram where [Fe/Mg] is plotted as a function of [Mg/H] (Fuhrmann 2000, Fig. 12). Fuhrmann's group of 16 thick disk stars have total space velocities with respect to the LSR in the range $85\,\mathrm{km\,s^{-1}} < V_{\mathrm{tot}} < 180\,\mathrm{km\,s^{-1}}$ and an average rotational lag of $V_{\mathrm{lag}} \simeq -80\,\mathrm{km\,s^{-1}}$. It is unclear if this low value is a selection effect.

On the basis of stellar ages derived from evolutionary tracks in M_{bol}- $\log T_{\mathrm{eff}}$ diagrams, Bernkopf, Fiedler, & Fuhrmann (2001) claim that the maximum age of thin disk stars is about 9 Gyr, whereas the thick disk stars have ages between 12 and 14 Gyr. These data agree well with their suggestion that the systematic difference of [α/Fe] is due to a hiatus in star formation between the thick and thin disk phases. However, Bernkopf et al. (2001) derived ages for 7 stars only. Larger samples of thick and thin disk stars should be dated before firm conclusions regarding a hiatus in star formation can be drawn.

Further evidence of a higher [α/Fe] in thick disk stars than in thin disk stars has been presented by Prochaska et al. (2000), who made a thorough study of the chemical composition of 10 G-type stars having $-1.2 <$ [Fe/H] < -0.4 and maximum orbital distances from the Galactic plane greater than 600 pc. Interestingly, [O/Fe], [Si/Fe], and [Ca/Fe] show a decline with increasing [Fe/H], which may be interpreted as a signature of enrichment of Type Ia SNe in the thick disk. This would mean that the thick disk formed over a time scale ≥ 1 Gyr. Prochaska et al. argue that such a formation time scale would rule out most dissipational collapse scenarios for the formation of the thick disk.

Recently, Feltzing, Bensby, & Lundström (2003) have found strong evidence for the presence of Type Ia SNe in the thick disk (see also papers at this meeting by Feltzing et al. 2004 and Bensby, Feltzing, & Lundström 2004). From a sample of about 14 000 dwarf stars in the solar neighborhood with metallicities and ages derived by Feltzing, Holmberg, & Hurley (2001), they selected two samples with a high kinematical probability of belonging either to

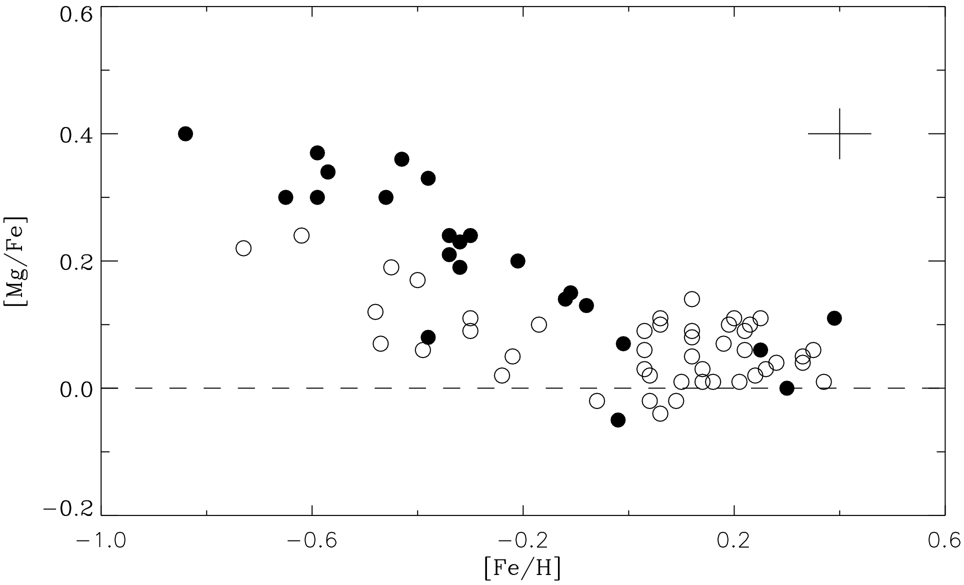

Fig. 1.2. [Mg/Fe] vs. [Fe/H] from Feltzing et al. (2003). Stars shown with filled circles have thick disk kinematics; open circles refer to thin disk stars.

the thin or the thick disk. When plotted in a Toomre diagram* (Feltzing et al. 2003, Fig. 1) it is seen that the thin disk stars have total space velocities $V_{\rm tot} < +60\,{\rm km\,s^{-1}}$, whereas the thick disk stars are confined to the range $80\,{\rm km\,s^{-1}} < V_{\rm tot} < 180\,{\rm km\,s^{-1}}$.

Interestingly, the thick disk stars of Feltzing et al. (2003) are distributed over the whole metallicity range from −1.0 to 0.0, and reach perhaps up to [Fe/H] $\simeq$ +0.4. Below [Fe/H] $\simeq$ –0.4, [α/Fe] in the thick disk stars is constant at a level of about 0.3 dex, and the thick disk is clearly separated from the thin disk in [α/Fe]. Above [Fe/H] = −0.4, [α/Fe] in the thick disk declines and the two disks merge together. This is seen for both Mg, Si, Ca, and Ti, but most clearly in [Mg/Fe], as shown in Figure 1.2. Hence, star formation in the thick disk went on long enough that Type Ia SNe started to enrich the gas out of which following generations of thick disk stars formed.

Attention is also drawn to a new work by Reddy et al. (2003). A sample of 181 F–G dwarfs were selected from the Olsen (1983, 1988) *uvby*-β catalogs, and the abundances of 27 elements were determined from high-resolution spectra. Parallaxes and proper motions were taken from the Hipparcos Catalogue (ESA 1997). Nearly all stars studied have thin disk kinematics. The α-elements, O, Mg, Si, Ca, and Ti, show [α/Fe] to increase slightly with decreasing [Fe/H] in the range –0.7 < [Fe/H] < 0.0. When compared with abundances for thick disk stars, mainly collected from Fulbright (2000), the thick disk stars have [α/Fe] about 0.15 dex higher than the thin disk stars in the overlap region around [Fe/H] $\approx$ –0.5. Hence, the new work of Reddy et al. supports the thick-thin α-element separation discussed in this section.

* Sandage & Fouts (1987) appear to be the first to apply this type of diagram in a discussion of the escape velocity of the Galaxy and to name it the "Toomre energy diagram," recognizing that the representation was due to A. Toomre (1980, private communication).

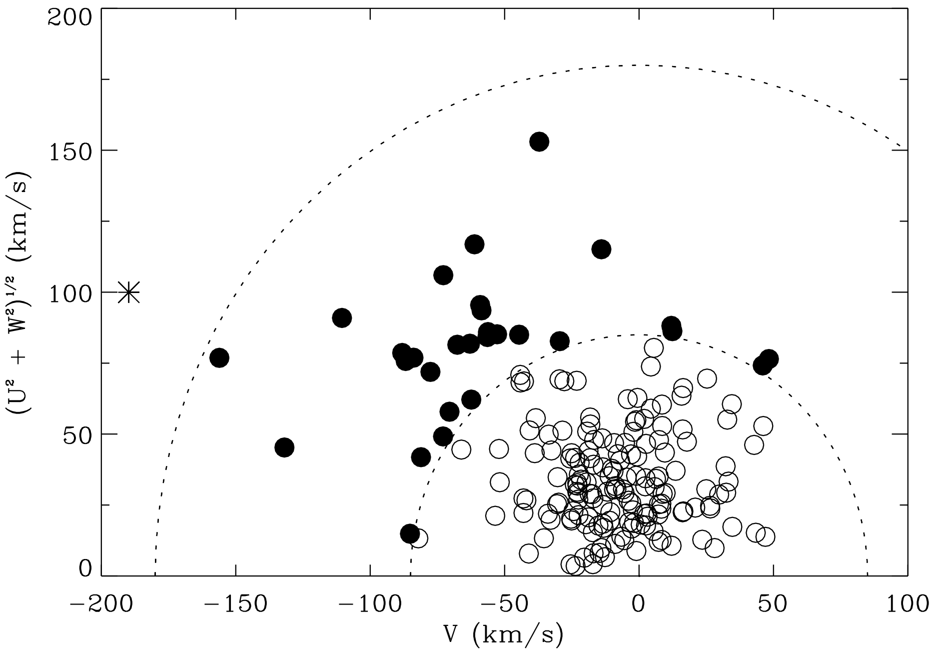

Fig. 1.3. Toomre diagram for the Edvardsson et al. stars. The two circles delineate constant total space velocities with respect to the LSR of $V_{\rm tot}$ = 85 and 180 km s^{-1}, respectively, as used by Fuhrmann (2000) to define a sample of thick disk stars. According to this definition, filled circles are thick disk stars, whereas open circles refer to thin disk stars. One star, HD 148816, shown by an asterisk, is classified as a halo star.

In view of these new results on the separation of [α/Fe] between thin and thick stars, it is interesting to see if the scatter in [α/Fe] for the Edvardsson et al. (1993) sample can be interpreted in terms of thick-thin differences, instead of a correlation with galactocentric distance (Fig. 1.1). To investigate this, I have plotted the Edvardsson et al. stars in a Toomre diagram (Fig. 1.3) and divided them into thin and thick disk stars according to the kinematical definitions of Fuhrmann (2000). As seen from Figure 1.4, much of the scatter can indeed be explained in terms of thick-thin differences in [α/Fe]. The separation is not quite as clear as seen in the diagrams of Fuhrmann (2000) and Feltzing et al. (2003), but this may be due to the fact that these authors have selected kinematically well-separated groups of stars, whereas the Edvardsson et al. sample is magnitude limited for a given metallicity bin and hence contains more stars with kinematics in the thick-thin transition region.

In a continuation of the work of Edvardsson et al., Chen et al. (2000) studied the chemical composition of 90 F and G dwarf stars. They do not find any clear [α/Fe] separation between thin and thick disk stars. As pointed out by Prochaska et al. (2000), this may, however, be due to the fact that they selected dwarf stars in the temperature range 5800 K $< T_{\rm eff} <$ 6400 K. Hence, the old, more metal-rich thick disk stars with $T_{\rm eff} <$ 5700 K are not included. The few thick disk stars in Chen et al. all have [Fe/H] < -0.6, i.e. they are lying in a metallicity region where [α/Fe] of the thin disk merges with [α/Fe] of the thick disk.

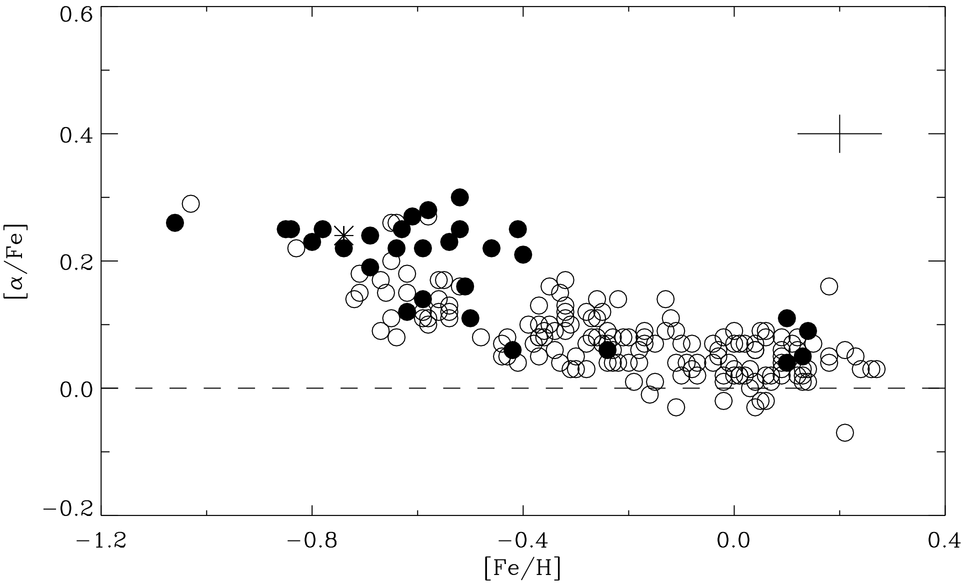

Fig. 1.4. [α/Fe] vs. [Fe/H] for the Edvardsson et al. (1993) stars. As classified in Fig. 1.3, filled circles are thick disk stars and open circles are thin disk stars. The asterisk shows HD 148816, the only halo star in the sample.

1.2.3 A Comparison With [α/Fe] *in Halo Stars*

Photometric and spectroscopic surveys of high-velocity, main sequence and subgiant stars in the solar neighborhood by Nissen & Schuster (1991), Schuster, Parrao, & Contreras Martínez (1993), and Carney et al. (1996) have shown that the metallicity range $-1.5 <$ [Fe/H] < -0.5 contains both halo stars having a small velocity component in the direction of Galactic rotation, $V_{\rm rot} < 50$ km s^{-1}(where $V_{\rm rot} = V + 225$ km s^{-1}), and thick disk stars with $V_{\rm rot} \simeq 175$ km s^{-1}. Nissen & Schuster (1997) selected such two groups of stars with overlapping metallicities, and used high-resolution, high signal-to-noise ratio spectra to determine abundance ratios of O, Na, Mg, Si, Ca, Ti, Cr, Fe, Ni, Y, and Ba with a differential precision ranging from 0.02 to 0.07 dex for 13 halo stars and 16 thick disk stars. Figure 1.5 shows the results for [O/Fe] and [Mg/Fe] vs. [Fe/H]. The same pattern is seen for the other α-elements, Si, Ca, and Ti, although with a smaller amplitude for the abundance variations with respect to Fe. As seen, all thick disk 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 the same abundance ratios as the thick disk stars. From this they suggest that the 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 (Gilmore & Wyse 1991; Tsujimoto et al. 1995; Pagel & Tautvaišienė 1998) predict a solar α/Fe ratio at [Fe/H] $\simeq -1.0$ as a consequence of an early star formation burst followed by a long dormant period. Recently, Shetrone et al. (2003) and Venn et al. (2004) have found that stars in dwarf spheroidal and irregular galaxies with metallicities around

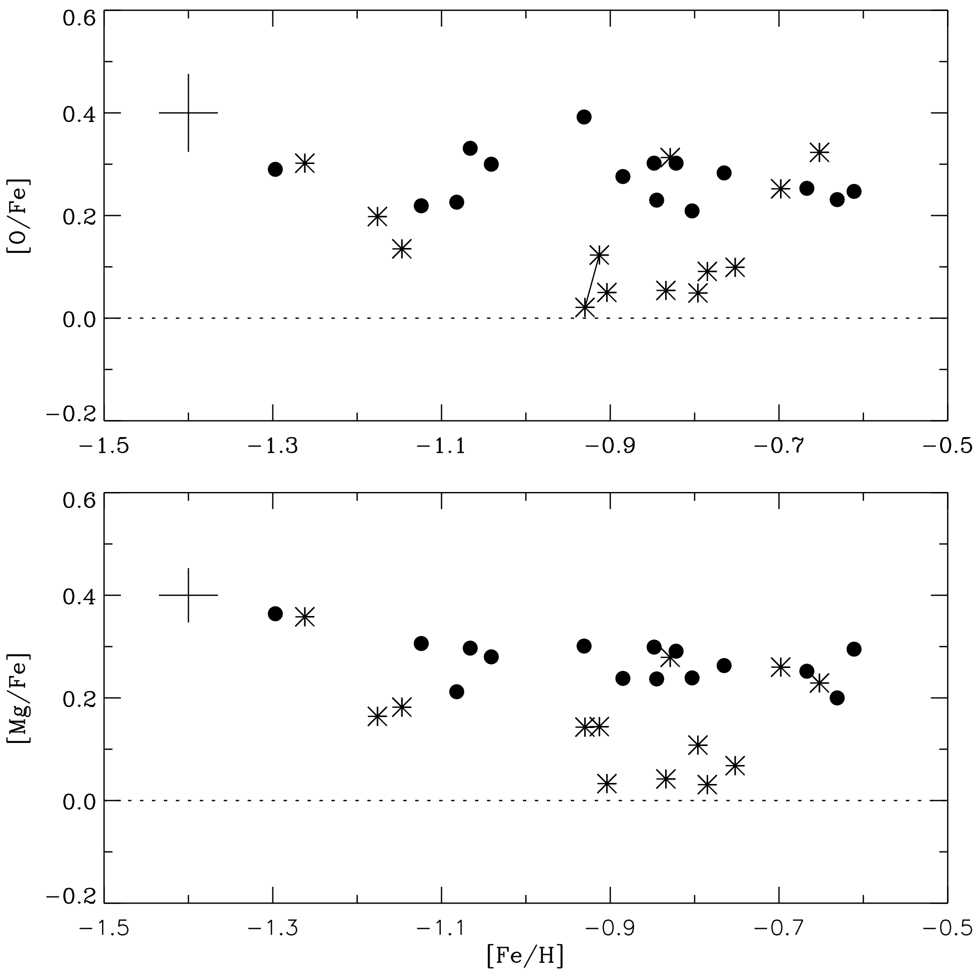

Fig. 1.5. [O/Fe] and [Mg/Fe] vs. [Fe/H] from Nissen & Schuster (1997). Filled circles refer to thick disk stars with a Galactic rotation velocity component $V_{\rm rot} > 150\,{\rm km\,s^{-1}}$, and asterisks refer to halo stars with $V_{\rm rot} < 50\,{\rm km\,s^{-1}}$. Two of the halo stars (connected with a line) are components in a spectroscopic binary.

[Fe/H] ≈ -1.0 indeed have a rather low [α/Fe] ratio, supporting the view that the low-[α/Fe] stars belong to an accreted halo component.

Jehin et al. (1999) found two additional halo stars at [Fe/H] $\simeq -1.1$ having low values of [α/Fe]. Among the more metal-poor halo stars with [Fe/H] < -1.4, α-poor stars are rare; only a couple of cases have been found (Carney et al. 1997; King 1997). A more systematic study by Stephens & Boesgaard (2002) of halo stars with unusual orbital properties, i.e. belonging to the "outer" or "high" halo, did not reveal any new α-poor stars, although a weak correlation between [α/Fe] and $R_{\rm apo}$ was detected.

Interestingly, the α-poor stars are also deficient in Na and Ni. Furthermore, there is a tight

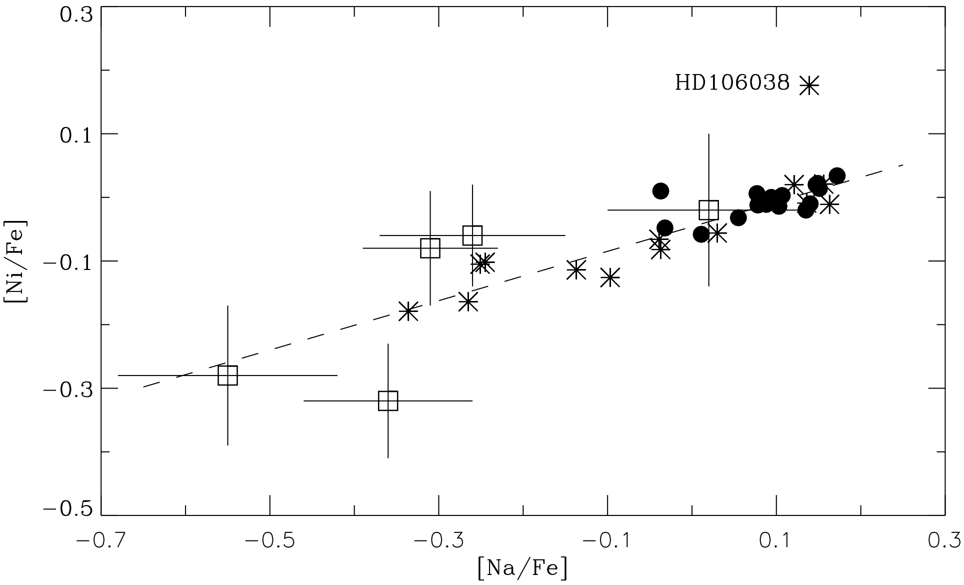

Fig. 1.6. [Ni/Fe] vs. [Na/Fe]. Filled circles refer to to thick disk stars and asterisks to halo stars with abundance ratios from Nissen & Schuster (1997). The dashed line is a fit to these data, excluding the peculiar star HD 106038. The squares with error bars are red giant stars in dwarf spheroidal galaxies with abundances determined by Shetrone et al. (2003) and with metallicities in the range $-1.4 < [Fe/H] < -0.6$.

correlation between [Ni/Fe] and [Na/Fe], as shown in Figure 1.6, except for one peculiar Ni-rich halo star, HD 106038, which is also very rich in Si and the *s*-process elements Y and Ba (Nissen & Schuster 1997). Furthermore, Figure 1.6 shows that dwarf spheroidal stars selected to have $-1.4 < [Fe/H] < -0.6$ tend to follow the relation delineated by the α-poor halo stars, hence supporting the idea that the α-poor stars are accreted from dwarf galaxies. The reason for the correlation between Na and Ni abundances is unclear, but it may be connected to the fact that the yields of both Na and the dominant Ni isotope (^{58}Ni) depend upon the neutron excess (Thielemann, Hashimoto, & Nomoto 1990).

1.3 Manganese and Zinc

Among the iron-peak elements, Cr and Ni follow Fe very closely (e.g., Chen et al. 2000), and there is no offset between thick and thin disk stars (Prochaska et al. 2000). Manganese, on the other hand, shows an interesting behavior. A detailed study of the trend of [Mn/Fe] in disk and metal-rich halo stars was published by Nissen et al. (2000) based on high-resolution observations of the Mn I λ6020 triplet. Nissen et al., however, applied outdated data for the hyperfine structure of the Mn I lines. Using modern hyperfine structure data, Prochaska & McWilliam (2000) found significant corrections to the [Mn/Fe] values of Nissen et al. (2000). In Figure 1.7 their revised data have been plotted with the same symbols as in previous figures for halo, thin disk, and thick disk stars. As seen, there is a steplike change in [Mn/Fe] at $[Fe/H] \simeq -0.6$. Thick disk stars with [Fe/H] below –0.6 have $[Mn/Fe] \simeq -0.3$, whereas thin disk stars with $-0.8 < [Fe/H] < -0.2$ have $[Mn/Fe] \simeq$

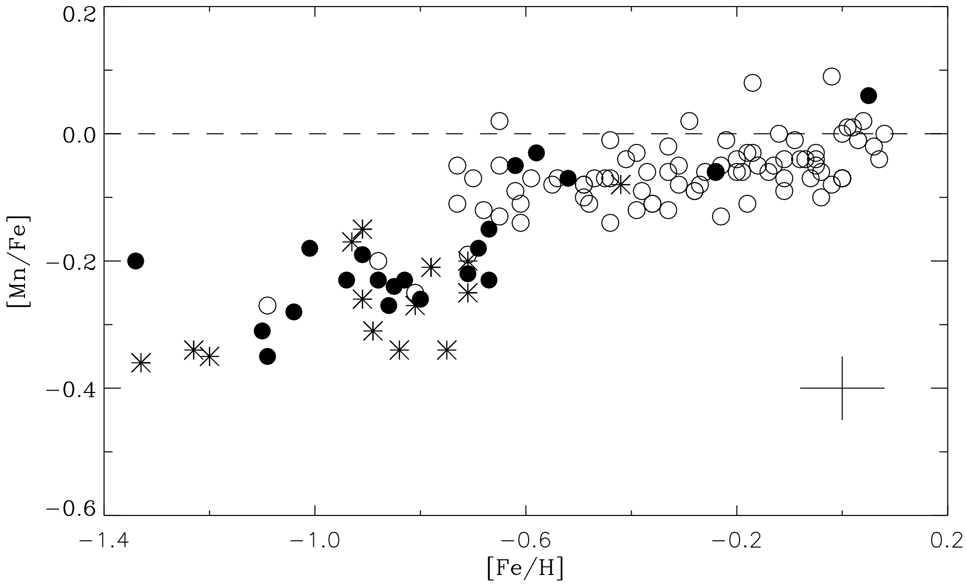

Fig. 1.7. [Mn/Fe] vs. [Fe/H] with data from Nissen et al. (2000), as corrected by Prochaska & McWilliam (2000). Open circles: thin disk; filled circles: thick disk; asterisks: halo stars.

–0.1. Due to the overlap in kinematics between the thick and the thin disk, the few stars with [Fe/H] $>$ –0.6 classified as thick disk may, in fact, belong to the high-velocity tail of the thin disk. The three stars with [Fe/H] $<$ –0.8 classified as thin disk have total space velocities with respect to the LSR close to the 85 km s^{-1} boundary that we have adopted as the separation velocity between the thick and the thin disk; i.e. they may belong to the thick disk. Altogether, the distribution of stars in Figure 1.7 may be interpreted as a separation in [Mn/Fe] between the thin and the thick disk.

The trend of [Mn/Fe] is close to mirror that of [α/Fe] with respect to the [X/Fe] = 0 line (compare Fig. 1.7 with Fig. 1.4). This suggests that Type Ia SNe is a main source for the production of Mn. On the other hand, the eight α-poor halo stars from Nissen & Schuster (1997), which are included in Figure 1.7, do not have higher [Mn/Fe] ratios than the thick disk stars, which one would have expected if Type Ia SNe were the main source of Mn production. Hence, it is not easy to understand the trend of [Mn/Fe]. Probably, the underabundance of Mn is partly caused by a metallicity-dependent yield due to a lower neutron excess in metal-poor stars (Timmes, Woosley, & Weaver 1995).

Zinc is an interesting element with a number of possible nucleosynthesis channels: neutron capture (*s*-processing) in low- and intermediate-mass stars, as well as explosive burning in Type II and Ia SNe (Matteucci et al. 1993). Furthermore, zinc is a key element in studies of elemental abundances of damped Lyα systems because Zn is practically undepleted unto dust (e.g., Pettini et al. 1999). In studies of damped Lyα systems, it is normally assumed that [Zn/Fe] $\simeq$ 0.0 in Galactic stars, as found by Sneden, Gratton, & Crocker (1991) for the range −3.0 $<$ [Fe/H] $<$ 0.0, although with quite a high scatter. Prochaska et al. (2000) claim, however, that Zn is overabundant in thick disk stars, [Zn/Fe] $\simeq$ +0.1. Recently, Mishenina

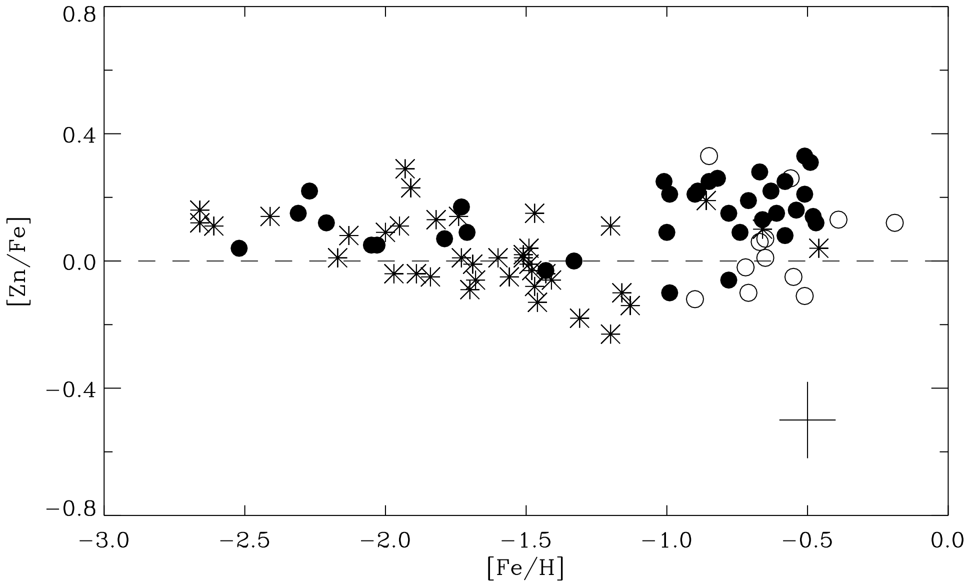

Fig. 1.8. [Zn/Fe] vs. [Fe/H] with data from Mishenina et al. (2002). Open circles: thin disk; filled circles: thick disk; asterisks: halo stars.

et al. (2002) have published a survey of Zn abundances in 90 disk and halo stars based on equivalent widths of the Zn I $\lambda\lambda$4722.2, 4810.5, 6362.4 lines in high-resolution spectra of dwarf and giant stars. Although the authors conclude that the data "confirms the well-known fact that the ratio [Zn/Fe] is almost solar at all metallicities," there is in fact a hint of interesting structure in their [Zn/Fe] trend. In Figure 1.8, I have plotted the data of Mishenina et al. (2002) using the total space velocity with respect to the LSR to separate the stars into the halo, thin, and thick populations, in the same way as in Figure 1.3. As seen, there is a tendency that thick disk stars in the metallicity range $-1.0 <$ [Fe/H] < -0.5 are overabundant in Zn by as much as [Zn/Fe] $\approx +0.2$. Furthermore, there may be a gradient in [Zn/Fe] as a function of [Fe/H] for the halo stars, with the highest [Zn/Fe] for the most metal-poor stars. Clearly, [Zn/Fe] in halo and disk stars should be further studied, if possible with smaller errors than those obtained by Mishenina et al. (2002).

An interesting detail from Figure 1.8 should be noted: stars classified as thick disk occur down to metallicities around [Fe/H] $\simeq -2.5$. Although it is difficult to distinguish between thick disk and halo stars due to their overlapping kinematics, it is interesting that studies of large samples of metal-poor stars selected without kinematical bias (Beers & Sommer-Larsen 1995; Chiba & Beers 2000) point to the existence of thick disk stars at a rate of $\sim$10% relative to the halo population in the range $-2.2 <$ [Fe/H] < -1.7 and $\sim$30% for $-1.7 <$ [Fe/H] < -1.0.

1.4 The *s*- and *r*-Process Elements

A very interesting set of papers on barium and europium abundances in cool dwarf stars have recently been published by Mashonkina & Gehren (2000, 2001) and Mashonkina

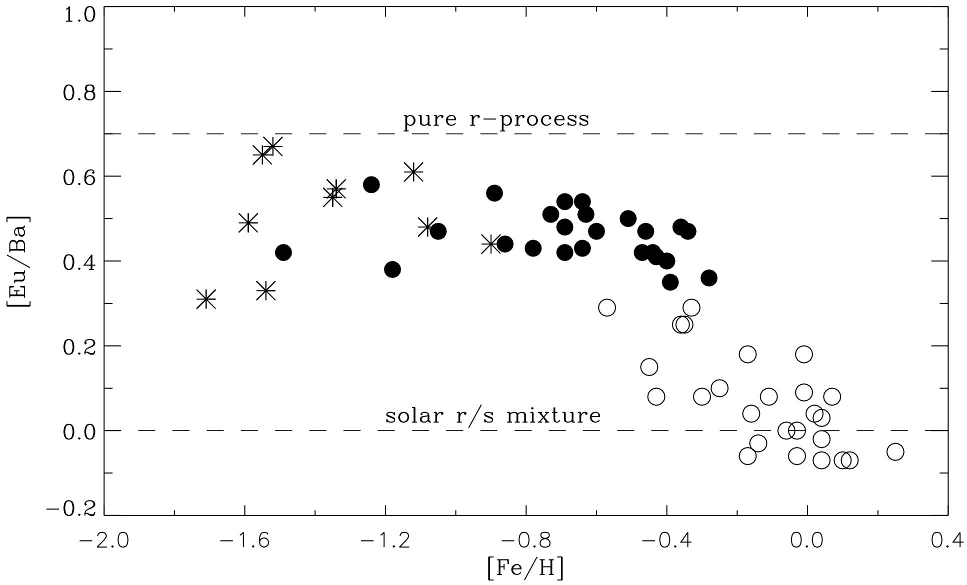

Fig. 1.9. [Eu/Ba] vs. [Fe/H] with data from Mashonkina & Gehren (2000, 2001) and Mashonkina et al. (2003). Open circles: thin disk; filled circles: thick disk; asterisks: halo stars.

et al. (2003). Their results are obtained from a non-LTE, differential model atmosphere analysis of high-resolution, high signal-to-noise ratio spectra of the Ba II $\lambda\lambda$ 5853, 6496 lines and the Eu II λ4129 line, taking into account hyperfine structure effects for the Eu line. Their data for the [Eu/Ba] ratio are plotted in Figure 1.9. As seen, there is a rather clear separation between thick and thin disk stars. While thin disk stars have a solar r/s mixture at solar metallicity, thick disk stars and some halo stars approach a pure *r*-process ratio. The steplike change in Eu/Ba around [Fe/H] ≈ -0.5 from the thick to the thin disk suggests a hiatus in star formation before the thin disk developed, i.e. long enough to enable low-mass asymptotic giant branch (AGB) stars to produce Ba by the *s*-process.

In addition to the separation in [Eu/Ba] between thick and thin disk stars, Mashonkina et al. (2003) claim that the slight decline in [Eu/Ba] with increasing [Fe/H] for the thick disk stars is significant. If real, this suggests a rather long time scale (1.1 to 1.6 Gyr) for the formation of the thick disk according to the chemical evolution calculations of Travaglio et al. (1999). Finally, a significant dispersion in [Eu/Ba] is seen for the halo stars, which suggests a duration of the halo formation of about 1.5 Gyr. Interestingly, Mashonkina et al. (2003) also find a dispersion in [Mg/Fe] for the halo stars. At [Fe/H] ≈ -1.0, the average [Mg/Fe] in halo stars is lower than in thick disk stars, a result that agrees well with the findings of Nissen & Schuster (1997).

1.5 Conclusions

We have seen that disk stars in the metallicity range $-0.8 <$ [Fe/H] < -0.4 have significant differences in the α-element/Fe abundance ratio, showing a variation of ~ 0.2 dex in [Mg/Fe] and about 0.15 dex in [Si/Fe], [Ca/Fe], and [Ti/Fe]. These differences were originally detected by Edvardsson et al. (1993) and interpreted by them as due to a radial gradient in the star formation rate in the Galactic disk causing the enrichment of iron-peak elements by Type Ia SNe to start at a higher [Fe/H] in the inner disk than in the outer regions. More recent work by Gratton et al. (1996, 2000), Fuhrmann (1998, 2000), Prochaska et al. (2000), Feltzing et al. (2003), and Reddy et al. (2003) suggests, however, that the differences are due to a chemical separation between thin and thick disk stars. Thereby, these investigations indicate that the thin and thick disks are discrete components, as originally suggested by Gilmore & Reid (1983) from a study of the distribution of stars in the direction of the Galactic South Pole, and as also supported by kinematical studies of unbiased samples of stars (e.g., Soubiran et al. 2003). Further evidence of a chemical separation of thin and thick disk stars is seen in [Mn/Fe] (Nissen et al. 2000; Prochaska & McWilliam 2000), in [Eu/Ba] (Mashonkina & Gehren 2000, 2001; Mashonkina et al. 2003), and perhaps in [Zn/Fe] (Mishenina et al. 2002). Hence, the evidence for a two-component (thin and thick disk) interpretation of the [α/Fe], [Mn/Fe], and [Eu/Ba] differences is quite compelling, although one should note that some of the studies mentioned have selected stars with extreme kinematics to make it possible to classify stars as belonging to either the thin or the thick disk population. If volume-limited samples of stars are selected, one may see more stars with intermediate abundance ratios, as suggested by the work of Edvardsson et al. (see Fig. 1.4).

As mentioned in the introduction, the survey of Edvardsson et al. (1993) suggests that thick disk stars are older than thin disk stars. Bernkopf et al. (2001) determined isochrone ages for a few of the stars from Fuhrmann (1998, 2000) and obtained ages between 12 and 14 Gyr for the thick disk stars, whereas the oldest thin disk stars have ages around 9 Gyr. This points to a hiatus in star formation between the thick and thin disk phases, which nicely explains the abrupt decline in [α/Fe]; during the hiatus, Type Ia SNe started to enrich the interstellar gas with iron-peak elements, whereas the production of α-capture elements by Type II SNe stopped. Similarly, the decline in [Eu/Ba] is due to enrichment of the interstellar gas with Ba from low-mass AGB stars, while the high-mass stars had ceased to contribute Eu.

The work of Feltzing et al. (2003) provides evidence that [α/Fe] in thick disk stars starts to decline at a metallicity [Fe/H] ≥ -0.4, and Mashonkina et al. (2003) found a hint for a decline of [Eu/Ba] among thick disk stars at the same metallicity. Hence, we may see a signature of the occurrence of the products of Type Ia SNe and low-mass AGB stars in the thick disk at [Fe/H] $\simeq -0.4$, suggesting that the thick disk phase lasted at least $\sim$1 Gyr.

As discussed in detail by Majewski (1993), there are two different classes of models for the formation of the thick disk: the pre-thin disk (top-down) models and the post-thin disk (bottom-up) models. Within the first class, the chemodynamical model of Burkert, Truran, & Hensler (1992) seems the most convincing. According to this model, the thick disk is a stage in the collapse of the Galaxy where a high star formation rate leads to a high energy input into the interstellar medium, halting the collapse and resulting in stars with a velocity dispersion $\sigma_W \approx 40\,\mathrm{km\,s^{-1}}$. As a result of metal enrichment, the cooling becomes more efficient, and the collapse continues forming the thin disk from inside-out. A difficulty with this model is that it predicts a thick disk phase with a duration of the order of 400 Myr only, i.e. shorter than estimated above from the signature of enrichment by Type Ia SNe and low-mass AGB stars in the thick disk. Also, it is not clear if the model would agree with a 1–2 Gyr hiatus in star formation between the thick and the thin disk.

Among the class of post-thin disk models, violent heating of the early thin disk due to merging of a major satellite galaxy (e.g., Quinn, Hernquist, & Fullagar 1993) is the most obvious possibility. The thick disk stars were originally formed in the ancient thin disk, with no tight limitations on the time scale for the chemical enrichment. After the merger, one can imagine that the star formation stopped for a while until the gas assembled again in a thin disk, causing the hiatus that is needed to explain the shift in [α/Fe] and [Eu/Ba] between the thick and the thin disk. Furthermore, if one assumes that the reestablished disk is formed from gas in the thick disk plus accreted metal-poor gas from the intergalactic medium, then one can explain why some thin disk stars have a lower metallicity than the maximum metallicity of the thick disk, i.e. the overlap of thin and thick disk stars in the metallicity range $-0.8 <$ [Fe/H] < -0.3.

As shown by Nissen & Schuster (1997), there is also an overlap in metallicity between halo and thick disk stars in the metallicity range $-1.4 <$ [Fe/H] < -0.6 with the majority of halo stars having lower [α/Fe], [Na/Fe] and [Ni/Fe] than thick disk stars. The low-[α/Fe] stars tend to be on larger Galactic orbits than halo stars having the same [α/Fe] as thick disk stars. The explanation may be that we have altogether two major components of our Galaxy: (1) a dissipative component consisting of the bulge, the *inner* halo, and the thick disk all formed in a collapse stage with a fast star formation rate enabling the metallicity to reach high values before Type Ia SNe and low-mass stars started to enrich the gas, and (2) an accreted *outer* halo plus the thin disk, where the star formation has proceeded on a longer time scale.

Much more work on stellar ages, kinematics, and abundances has to be carried out before we can be sure about the basic scenario for the formation and evolution of our Galaxy. Many of the results, quoted above, are based on studies of the chemical composition of kinematically selected samples of stars. Thereby, the conclusions may be affected by a kinematical bias, which, for example, exaggerates the chemical separation between thick and thin disk stars. To avoid this, it would be interesting to conduct an age-kinematics-abundance survey of, say, the 20 brightest stars in each of 25 metallicity groups spanning the range $-2.0 <$ [Fe/H] $< +0.5$ (i.e. a total of 500 stars), which should be selected to lie on the main sequence and in the temperature range $5000\,\mathrm{K} < T_{\mathrm{eff}} < 6500$ K. It would also be very interesting to make *in situ* studies of abundances and kinematics of stars in the inner and outer halo, and at various places in the thin and thick disk. Such studies may well give some surprises. Thus, Gilmore, Wyse, & Norris (2002) have recently conducted a low-resolution spectroscopic survey of ~ 2000 F–G stars situated 0.5–5 kpc from the Galactic plane, and have found evidence that the mean rotation velocity a few kpc away from the Galactic plane is $\sim 100\,\mathrm{km\,s^{-1}}$ rather than the predicted $\sim 175\,\mathrm{km\,s^{-1}}$ from the local thick disk population. Gilmore et al. propose that their outer sample is dominated by the debris stars from the disrupted satellite that formed the thick disk. Clearly, it would be very interesting to investigate the chemical composition of such stars in detail.

References

Baranne, A., et al. 1996, A&AS, 119, 373

Beers, T. C., & Sommer-Larsen, J. 1995, ApJS, 96, 175

Bensby, T., Feltzing, S., & Lundström, I. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/symposia/series/symposium4/proceedings.html)

Bernkopf, J., Fiedler, A., & Fuhrmann, K. 2001, in Astrophysical Ages and Time Scales, ed. T. von Hippel, N. Manset, & C. Simpson (San Francisco: ASP), 207

Burkert, A., Truran, J. W., & Hensler, G. 1992, ApJ, 392, 651
Carney, B. W., Laird, J. B., Latham, D. W., & Aguilar, L. A. 1996, AJ, 112, 668
Carney, B. W., Wright, J. S., Sneden, C., Laird, J. B., Aguilar, L. A., & Latham, D. W. 1997, AJ, 114, 363
Chen, Y. Q., Nissen, P. E., Zhao, G., Zhang, H. W., & Benoni, T. 2000, A&AS, 141, 491
Chiba, M., & Beers, T. C. 2000, AJ, 119, 2843
Edvardsson, B., Andersen, J., Gustafsson, B., Lambert, D. L., Nissen, P. E., & Tomkin, J. 1993, A&A, 275, 101
ESA 1997, The Hipparcos and Tycho Catalogues, ESA SP-1200
Feltzing, S., Bensby, T., Gesse, S., & Lundström, I. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/symposia/series/symposium4/proceedings.html)
Feltzing, S., Bensby, T., & Lundström, I. 2003, A&A, 397, L1
Feltzing, S., Holmberg, J., & Hurley, J. R. 2001, A&A, 377, 911
Freeman, K. C. 1991, in Dynamics of Disk Galaxies, ed. B. Sundelius (Göteborg: Göteborg Univ.), 15
Fuhrmann, K. 1998, A&A, 338, 161
Fuhrmann, K. 2000, http://www.xray.mpe.mpg.de/∼fuhrmann
Fulbright, J. P. 2000, AJ, 120, 1841
Gilmore, G., & Reid, N. 1983, MNRAS, 202, 1025
Gilmore, G., & Wyse, R. F. G. 1991, ApJ, 367, L55
Gilmore, G., Wyse, R. F. G., & Norris, J. E. 2002, ApJ, 574, L39
Gratton, R., Caretta, E., Matteucci, F., & Sneden, C. 1996, in Formation of the Galactic Halo, ed. H. Morrison & A. Sarajedini (San Francisco: ASP), 307
——. 2000, A&A, 358, 671
Høg, E., et al. 2000, A&A, 355, L27
Jehin, E., Magain, P., Neuforge, C., Noels, A., Parmentier, G., & Thoul, A. A. 1999, A&A, 341, 241
King, J. R. 1997, AJ, 113, 2302
Majewski, S. R. 1993, ARA&A, 31, 575
Mashonkina, L., & Gehren, T. 2000, A&A, 364, 249
——. 2001, A&A, 376, 232
Mashonkina, L., Gehren, T., Travaglio, C., & Borkova, T. 2003, A&A, 397, 275
Matteucci, F., Raiteri, C. M., Busso, M., Gallino, R., & Gratton, R. 1993, A&A, 272, 421
Mishenina, T. V., Kovtyukh, V. V., Soubiran, C., Travaglio, C., & Busso, M. 2002, A&A, 396, 189
Ng, Y. K., & Bertelli, G. 1998, A&A, 329, 943
Nissen, P. E. 1995, in IAU Symp. 164, Stellar Populations, ed. P. C. van der Kruit & G. Gilmore (Dordrecht: Reidel), 109
Nissen, P. E., Chen, Y. Q., Schuster, W. J., & Zhao, G. 2000, A&A, 353, 722
Nissen, P. E., & Edvardsson, B. 1992, A&A, 261, 255
Nissen, P. E., Primas, F., Asplund, M., & Lambert, D. L. 2002, A&A, 390, 235
Nissen, P. E., & Schuster, W. J. 1991, A&A, 251, 457
——. 1997, A&A, 326, 751
O'Connell, D. J. K., ed. 1958, Stellar Populations, Vatican Observatory (Amsterdam: North Holland Publ. Comp.)
Olsen, E. H. 1983, A&AS, 54, 55
——. 1988, A&A, 189, 173
Pagel, B. E. J., & Tautvaišienė, G. 1998, MNRAS, 299, 535
Pettini, M., Ellison, S. L., Steidel, C. C., & Bowen, D. V. 1999, ApJ, 510, 576
Prochaska, J. X., & McWilliam, A. 2000, ApJ, 537, L57
Prochaska, J. X., Naumov, S. O., Carney, B. W., McWilliam, A., & Wolfe, A. M. 2000, AJ, 120, 2513
Quillen, A. C., & Garnett, D. R. 2001, in Galaxy Disks and Disk Galaxies, ed. J. G. Funes & E. M. Corsini (San Francisco: ASP), 87
Quinn, P. J., Hernquist, L., & Fullagar, D. P. 1993, ApJ, 403, 74
Reddy, B. E., Tomkin, J., Lambert, D. L., & Allende Prieto, C. 2003, MNRAS, 340, 304
Sandage, A., & Fouts, G. 1987, AJ, 93, 74
Schuster, W. J., Parrao, L., & Contreras Martínez, M. E. 1993, A&AS, 97, 951
Shetrone, M., Venn, K. A., Tolstoy, E., Primas, F., Hill, V., & Kaufer, A. 2003, AJ, 125, 684
Sneden, C., Gratton, R. G., & Crocker, D. A. 1991, A&A, 246, 354
Soubiran, C., Bienaymé, O., & Siebert, A. 2003, A&A, 398, 141
Stephens, A., & Boesgaard, A. M. 2002, AJ, 123, 1647
Strömgren, B. 1966, ARA&A, 4, 433

——. 1987, in The Galaxy, ed. G. Gilmore & B. Carswell (Dordrecht: Reidel), 229
Thielemann, F.-K., Hashimoto, M., & Nomoto, K. 1990, ApJ, 349, 222
Timmes, F. X., Woosley, S. E., & Weaver, T. A. 1995, ApJS, 98, 617
Tomkin, J., Lemke, M., Lambert, D. L., & Sneden, C. 1992, AJ, 104, 1568
Travaglio, C., Galli, D., Gallino, R., Busso, M., Ferrini, F., & Straniero, O. 1999, ApJ, 521, 691
Tsujimoto, T., Nomoto, K., Yoshii, Y., Hashimoto, M., Yanagida, S., & Thielemann, F.-K. 1995, MNRAS, 277, 945
Venn, K. A., Tolstoy, E., Kaufer, A., & Kudritzki, R. P. 2004, in Carnegie Observatories Astrophysics Series, Vol. 4: Origin and Evolution of the Elements, ed. A. McWilliam & M. Rauch (Pasadena: Carnegie Observatories, http://www.ociw.edu/symposia/series/symposium4/proceedings.html)
Zhao, G., & Magain, P. 1990, A&AS, 86, 65