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Thin and Thick Disk Results for α-, r- and s-Process Elements

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Abstract

We present the first results from several ongoing studies of the stellar abundances, ages, and chemical trends in the long-lived dwarf stars in the solar neighborhood that belong to the thin and thick galactic disk. We confirm that the trends of α-elements in the thin and thick disk are distinct, and we also find that the thick disk show the typical signature of SN Ia contribution to the chemical enrichment of the interstellar gas out of which the later generations of thick disk stars formed. From a first study of the r- and s-process elements we report preliminary evidence that AGB stars also have contributed to the chemical enrichment in the thick disk. Furthermore, we investigate the individual as well as the collective ages of the thick disk stars and find evidence of an overall age-metallicity relation in the thick disk. This has, to our best knowledge, not been shown before. All this indicate that the star formation in what is today's thick disk was extended over time and, at least for the stars that are today close to the sun, the gas which the stars formed out of was well-mixed. These findings seem to rule out scenarios where the thick disk formed in a fast dissipative collapse.

1.1 Introduction

It was revealed in the 1980s, by Gilmore & Reid (1983), that our Galaxy, like many other spiral galaxies, has a thick disk. Further studies of the thick disk stars have shown them to be distinct from the thin disk and the halo stars in terms of kinematic properties as well as mean metallicity. All evidence indicate that the thick disk is older than the thin disk. Recently it has been established that the elemental abundance trends for stars in the thin and the thick disk are different. Most studies have focused on the α-elements, e.g. Gratton et al. (2000), Fuhrmann (1998), and Feltzing et al. (2003). Common to these studies are that they do a differential study, i.e. stars from both disks are studied with the same equipment and the same analysis is applied to the spectra. This is important since systematic errors are minimized. The studies agree that the trends in the thin and the thick disks are different.

Furthermore, Feltzing et al. (2003) probe the thick disk to higher metallicities than the other studies, all the way up to solar metallicity, and find that there is evidence for SN Ia contribution to the chemical enrichment of the material that the most metal-rich thick disk stars formed out of. Here we will discuss those results and also present the first results from a pre-study of the r- and s-process elements and some speculative interpretations of these results. We also discuss the age of the thick disk and end with an overview of possible formation scenarios for the thick disk.

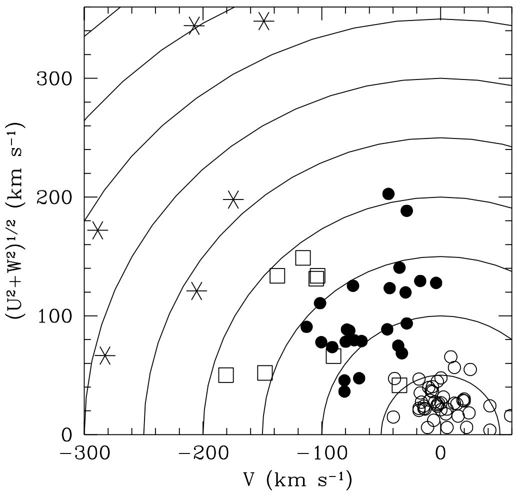

Fig. 1.1. Toomre diagram for our and Fuhrmann (1998) stars. Our thin disk stars are denoted by ∘ and thick disk stars with •. Fuhrmann's thick disk stars are shown as □ and his halo stars as ∗.

1.2 Stellar Sample and Method of Analysis

Stars, for our abundance study, were selected based on their kinematic properties. In particular we used the catalog compiled by Feltzing & Holmberg (2000). Those velocities were used in combination with the velocity dispersions for the thin and thick disks, and the halo to calculate probabilities that each star belong to either component. We selected only stars that had a very high probability to belong to either the thin or the thick disk. When selecting stars we tried to cover the metal-poor thin disk and the thick disk with even numbers of stars per metallicity bin. We also explicitly looked for thick disk stars with high metallicities. In this way we created a sample of 24 thick disk and 43 thin disk stars. The kinematic data are shown in Fig. 1.1 where we also compare the kinematics to those of the thick disk and halo stars in Fuhrmann (1998). All stars in our sample have parallaxes measured by the Hipparcos satellite with errors < 5 %.

The full details of our analysis as well as abundances of iron-peak and other elements will be presented in Bensby, et al. (2003, submitted). Briefly, we perform a standard LTE analysis based on equivalent widths, compare e.g. Edvardsson et al. (1993). Model atmospheres are created using the Uppsala MARCS code, Gustafsson et al. (1974) and Edvardsson et al. (1993). For our pre-study of four r- and s-process elements we used spectrum synthesis when appropriate.

1.3 Results for α-elements

Figure 1.2 shows the abundance results for the two of the α-elements, Si and Mg. The first thing to notice is the separation of the trends for two samples, the thin and thick disks. The thick disk stars are, for a given [Fe/H], more abundant than the thin disk stars. Ti and Ca essentially show the same trends. The most metal-rich stars that are designated thick disk stars (at ~ 0.35 dex) could be possible interlopers from the inner disk (they have

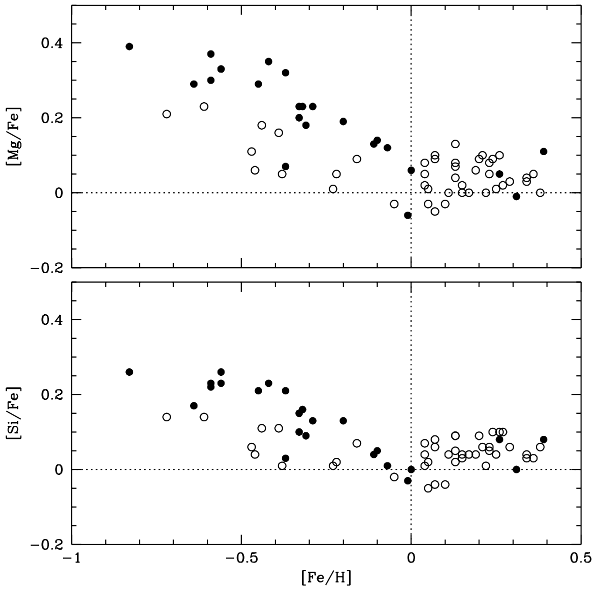

Fig. 1.2. [Mg/Fe] and [Si/Fe] as a function of [Fe/H] for our FEROS sample, Feltzing et al. (2003). • show the thick disk stars and ∘ the thin disk stars. Our result confirms and extends Fuhrmann (1998) results to all α-elements and to higher metallicities, see Feltzing et al. (2003) and Bensby et al. (2003, submitted)

rather low W_{LSR} velocities) rather than true thick disk stars. For an in-depth discussion of these stars see Bensby et al. (2003, submitted).

For the thick disk we see a constant [Mg/Fe] at lower metallicities and then from [Fe/H]$\sim$ -0.35 dex we see a downward trend. In the standard picture of chemical enrichment this downward trend is interpreted as contribution from SN Ia. Mg and Fe are both made in SN II and as long as those are the only contribution to the chemical enrichment the ratio between Mg and Fe remains unchanged. However, if star formation continues long enough there will be time for SN Ia to contribute. As Fe but not Mg are produced in SN Ia the [Mg/Fe] ratio will start to decline. The same is true for the other α-elements as illustrated for Si in Fig. 1.2. First results for oxygen are presented in Bensby et al. (2003).

The time at which the decline starts is not only a function of the lifetime of SN Ia but also of the SN Ia rate. The exact model, and hence lifetime for SN Ia, is still debated. The two most probable scenarios are a single or double degenerate system consisting of either two white dwarfs or a white dwarf and a red giant. In the latter case the life time is set by the main sequence lifetime of the star that becomes the red giant, while in the first case the lifetime for the system prior to become supernova is set by the time it takes them to spiral in and coalesce, and hence it depends on the initial separation and could be longer than the Hubble time. For a recent, in-depth discussion of these issues see Livio (2001). This uncertainty means that any interpretation of our α-abundance trends in terms of a minimum timescale for the star formation period in the thick disk will be rather complex and requires

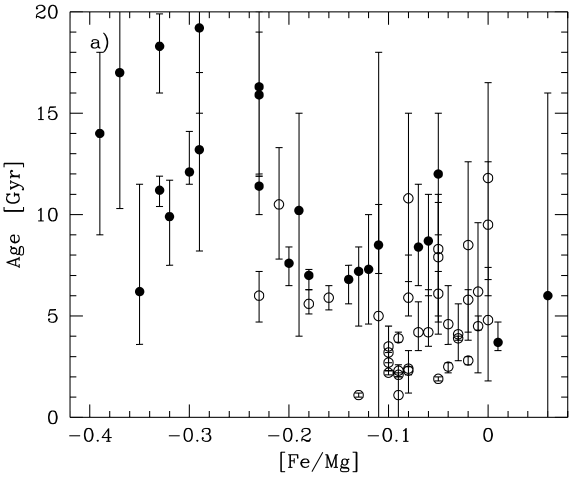

Fig. 1.3. Stellar ages as a function of [Fe/Mg] for all our stars which are evolved enough that stellar ages can be determined from isochrones (Bensby et al. 2003, submitted)

both a detailed model of the chemical evolution which explores the different possibilities that the different SN Ia scenarios allow.

1.4 Ages

1.4.1 Individual Stellar Ages

We have estimated the ages of our stars using isochrones from Girardi et al. (2000) for stars with no α-enhancement, and isochrones ($[\alpha/\mathrm{Fe}] \simeq 0.35$) from Salasnich et al. (2000) for stars with α-enhancements. As an approximate dividing limit, we treated stars with $[\mathrm{Mg/Fe}] \gtrsim 0.1$ as being α-enhanced. For stars within ± 0.05 dex of this limit we determined ages from both sets of isochrones and adopted the mean value. Lower and upper age limits were estimated from errors-bars representing the uncertainties in the stellar parallaxes and effective temperatures. Stars that are not sufficiently evolved, i.e. still on the main sequence, do not have age estimates. Figure 1.3 show our results.

We find average ages of 4.9±2.8 Gyr and 10.8±4.3 Gyr for the thin and thick disks, respectively (Bensby et al. 2003, submitted). In Feltzing et al. (2003) we quoted slightly higher average ages of 6.1±2.0 Gyr and 12.1±3.8 Gyr for the same stellar samples since we there used the ages from Feltzing et al. (2001) which did not include α-enhanced isochrones. The effect of using α-enhanced isochrones is in general to produce lower ages than when using isochrones without α-enhancement. Note also that here we use the spectroscopic T_{eff} and [Fe/H], which for individual stars can have an impact on the derived age. However, the mean ages of the two populations are still separated but we do note that there might be the possibility of overlapping ages distributions.

1.4.2 Age of the Thick Disk

In Fig. 1.4a we show all stars in our catalog that have thick disk kinematics. The most obvious feature of this diagram is that it shows an exclusively old stellar population.

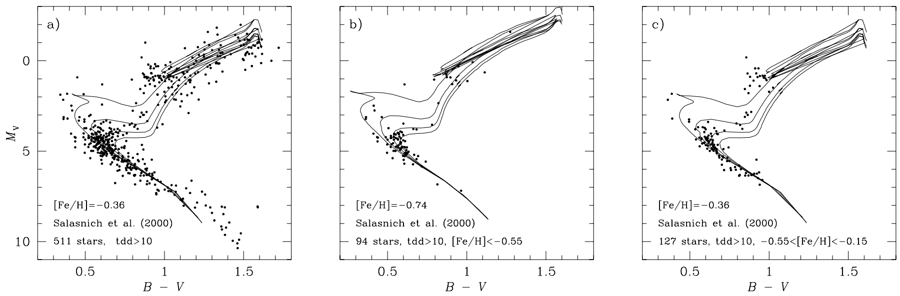

Fig. 1.4. HR-diagrams for kinematically selected samples of the thick disk with isochrones from Salasnich et al. (2000) for 2.5., 5, 10, and 15 Gyr. **a** shows all stars in our catalog that have thick disk kinematics. **b** and **c** show stars with thick disk kinematics and with metallicity estimates from Strömgren photometry. **b** shows stars with [Fe/H]<–0.55 plus isochrones for –0.74 dex and **c** stars with –0.55<[Fe/H]<–0.15 isochrones for –0.36 dex, Bensby et al. (in prep.)

In general the thick disk is enhanced in α-elements and therefore we may get a first estimate of the age and age-spread in the thick disk by comparing with the α-enhanced isochrones from Salasnich et al. (2000). The isochrones shown are for 2.5, 5, 10 and 15 Gyr and –0.36 dex. The thick disk then appears to first order to have stars as old as the oldest isochrones and the youngest turn-off is probably about 5 Gyr. There are a few stars with bluer colors, they could be either blue stragglers or interloping thin disk stars.

A subset of stars in our catalog have Strömgren photometry available from the literature. From the Strömgren photometry we can estimate the metallicity of the stars (see e.g. Feltzing et al. 2001). We then divide the thick disk sample into two, stars with [Fe/H]< –0.55 dex and stars with –0.55<[Fe/H]<–0.15 dex, Fig. 1.4 b and c. The samples contains 94 and 127 stars, respectively. Isochrones shown are for the same ages as before and for –0.74 and –0.36 dex, respectively. Here, we see something very interesting – the more metal-poor thick disk appears to be older than the more metal-rich thick disk. This, we believe, is the first real evidence for an overall age-metallicity relation in the thick disk. The metal-poor sample shows a turn-off between 10 and 15 Gyr while the more metal-rich sample has a turn-off between 5 and 10 Gyr. This would indicate a rather long time scale for the formation of the thick disk.

1.5 Results for *r*- and *s*-Process Elements

Not all elements are produced in SN II and SN Ia. A large number of elements are produced through the s-process, which operates at neutron fluxes low enough that β-decays can take place before the next neutron capture. Such fluxes can be found in asymptotic giant branch stars (AGBs). In recent years it has become clear that it is the low mass (1-3 $M_\odot$) AGBs that are the main providers of s-process elements (see e.g. Busso et al. 1999, Busso et al. 2001). However, most of the neutron capture elements are produced by both the r- and the s-process. The r-process requires a high flux of neutrons. This is available in the explosive nucleosynthesis in SN II. For example Burris et al. (2000) estimate that the s-process contributes 72% and 81% to the solar Y and Ba abundances, 47 % to the Nd abundance and only 3 % to the Eu abundance while the r-process contributes the remainder.

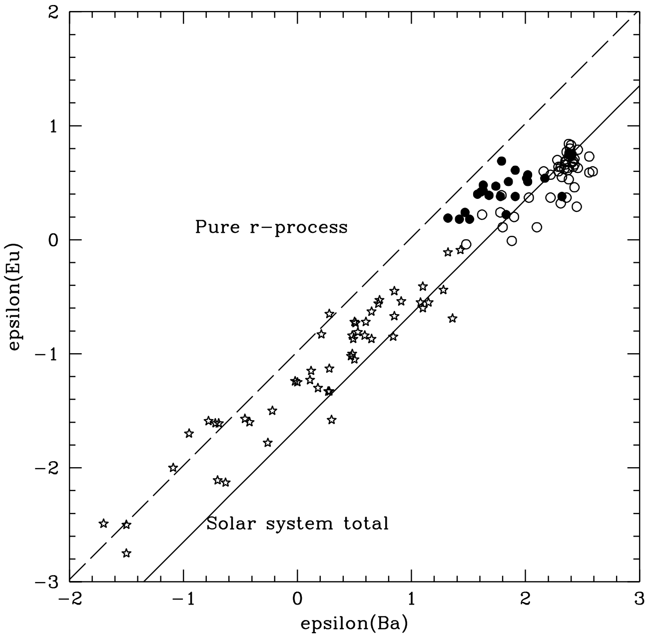

Fig. 1.5. Results from our pre-study illustrate the relative contributions from the r- and the s-process to Eu and Ba. The dashed line show the pure r-contribution to Eu and Ba while the full line show the solar system mix of r- and s-process contributions. The relations are adopted from Burris et al. (2000). ⋆ denote the data from Burris et al. (2000) and • our thick disk stars and ◦ our thin disk stars.

In order to see if we at all could use the s-process elements to further constrain the duration of the star formation epoch of the thick disk we have undertaken a pre-study of a few representative elements from our FEROS spectra. These spectra are not ideal for this task and we were e.g. only able to analyze one Eu line and one Y line. Still the results are intriguing and have lead us to obtain more suitable data. Here we report the results from our FEROS spectra.

1.5.1 First Results and a Speculative Interpretation

In Fig. 1.5 we compare our Eu and Ba data with predictions for pure r-process composition (as seen in the galactic halo) and solar system mix of r- and s-process contributions. The thin disk shows a solar system mix for all metallicities while the thick disk has not yet experienced the full contribution of s-processed material from the low mass AGB stars, i.e. it is closer to the pure r-process line. However, the scatter is, especially for the metal-poor thin disk stars, substantial. This is mainly due to the fact that the only usable Eu line (at 6645 Å) in our FEROS spectra is weaker in these stars, i.e. they have low Eu abundances. Forthcoming data with appropriate S/N should cure this problem.

A first, tentative interpretation of these results is that star formation went on long enough in the thick disk that AGB stars started to contribute to the chemical enrichment but only just

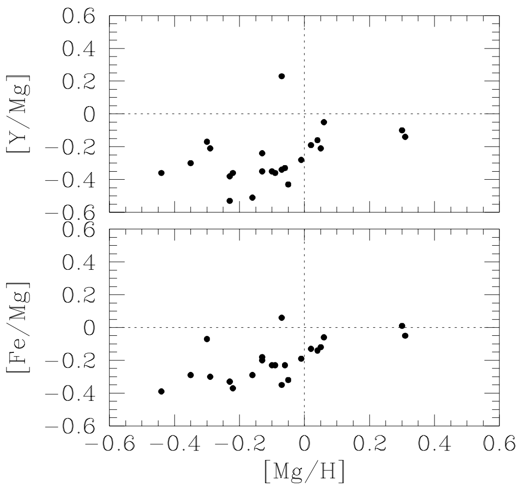

Fig. 1.6. Y and Fe abundances as a function of Mg for the thick disk

long enough that a solar system mix of r- and s-contributions was reached since there are a few thick disk stars that reach the solar line. However, this should be seen as a preliminary result due to the fairly large observational scatter. After the formation of stars stopped in the thick disk (due to a merger?) the gas settled into a new thinner disk. Most likely, fresh material of lower metallicity was accreted (from the galaxy causing the puff up of the thick disk?) and diluted the metallicity in the gas. However, the r- and s-process relative contribution to the elements will not change (if the accreted gas is close to primordial) so the first thin disk stars to form will retain the mix that was at the end of star formation in the thick disk. Obviously, at this stage this scenario is a speculation and would need further confirmation both theoretically and observationally.

1.5.2 How r- and s-Process Elements Could be Used to Constrain SN Ia Lifetimes

How the r- and s-process can be used to put further constraints on SN Ia progenitors and the nucleosynthesis in the low mass AGB stars is illustrated in Figs. 1.6 & 1.7. Here we use Mg as the reference element rather than the customary Fe. The reason for this is that Mg has one source, SN II, while Fe has two, SN Ia and SN II. If we use Mg as the reference element the interpretation is therefore much simplified. First consider the plots for Y and Fe in the thick disk, Fig. 1.6. [Y/Mg] appears to show an upward turn just above solar [Mg/H]. We interpret this as the onset of serious AGB contribution to the enrichment and possibly also a reflection of the metallicity of the stars that become AGB stars (see Busso et al. 2001). Y also has an r-process component, hence the flat trend at lower metallicities. The [Fe/Mg] abundance starts to increase, due to the onset of SN Ia, at the same [Mg/H]. Thus given a model for the star formation in the thick disk and knowledge of the lifetimes for the AGB stars that produce the Y we should be able to put a rather firm constraint on the SN Ia lifetime and SN Ia rate. We plan to develop such models.

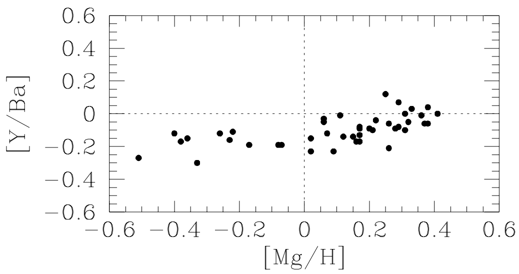

Fig. 1.7. Y relative to Ba as a function of Mg in the thin disk

1.5.3 Nuclesosynthesis in Low-mass AGB

A very interesting result is found when we study the trend of [Y/Ba] in the thin disk, Fig. 1.7. This trend is first flat but after solar metallicity a gentle upward trend is seen – this could be nicely explained as a metallicity effect in the AGB nucleosynthesis, Busso et al. (2001). Fig. 1 in Busso et al. shows how the relative production of the light (e.g. Y) and heavy (e.g. Ba) s-process elements change as a function of metallicity. For metallicities below solar the ratio is roughly flat, i.e. Y and Ba are produced in the same ratio in the low mass AGB stars. However, around solar metallicity this balance changes such that the lighter s-process elements are favored over the heavy s-process elements. Hence [Y/Ba] increases. We anticipate that by studying a large number of the light (Sr, Y, Zr, Nb) and heavy (Ba, La, Hf, Ce, Nd) s-process elements in the metal-rich thin disk we should be able to confirm or refute the predictions of such AGB models as presented in Busso et al. (2001).

1.5.4 Other Studies of r- and s-Process Elements in the Thin and Thick Disks

To our knowledge there is one other group that recently have studied the r- and s-process elements in the thin and thick disk and it seems that our results are contradictory to theirs: Mashonkina & Gehren (2001) have shown how the ratio of *r*- and *s*-process elemental abundances can be used to further constrain the star formation time. For the Bernkopf et al. (2001) stars Mashonkina & Gehren (2001) find that the *s*-process has not have had time to contribute and hence the lifetime of the AGB stars is longer than the star formation time-scale in the thick disk. Since their sample only contained stars with metallicities up to roughly –0.35 dex and hence they could not trace the trends up to solar metallicity in the way we have been able to do.

1.6 How Did the Thick Disk Form?

Our first and most important result is that the two disks show distinct abundance patterns for elements formed in several different processes. This should rule out any model that predict that the disks should have continuous distributions, e.g. diffusion of orbits or direct accretion of thin disk material.

Our second key result is that star formation went on long enough that SN Ia started to enrich the gas out of which sub-sequent generations of stars formed in what is today the thick disk. Given a model for SN Ia enrichment this sets a lower limit to how long time star formation went on for in the thick disk.

What is long-enough? Often a value of 1 Gyr is quoted as the time-scale for SN Ia to contribute to the chemical enrichment, however, this number is model dependent. The most important parameter, given a model for SN Ia, that sets this time-scale is the star-formation *rate*. This is illustrated in Matteucci (2001, Fig. 5.7, see also references therein) where they show how, in a bursting scenario, the SN Ia rate peaks significantly earlier than in e.g. the typical solar neighborhood (modeled to fit the over-all trends in the stellar abundances, as our results demonstrate such a simplification is not any longer fully valid). In fact it might be just possible to squeeze it in to the 400 Myr found for the rapid collapse model by Burkert et al. (1992). In the merger scenario the star formation in what later became the thick disk could have had at least a few Gyr to proceed and thus SN Ia may have contributed to the enrichment of the gas out of which the later generations of stars in today's thick disk formed. In summary, the presence of SN Ia signatures is not a strong enough constraint to distinguish between a rapid collapse or a violent merger.

The lack of a vertical abundance gradient is often quoted as supporting a merger scenario. However, if there are gradients present in the disk prior to the merger they will remain after the merger (Quinn et al. 1993). Furthermore, if the thin disk is around 7 Gyr old and the merger took about 1–3 Gyr to complete (Quinn et al. 1993) then there would be ample time left over to let the original thin disk form through a slow, dissipative collapse. Moreover, Burkert et al. (1992) show that in the rapid collapse model it is possible to have no vertical gradient over a fairly large height.

First results from our study of the trends for the r- and s-process elements in the thin and thick disks appears to indicate that star formation went on long enough so that AGB stars had time to contribute to the chemical enrichment in the thick disk. Since the time-scale for low mass AGB stars is significant this might pose a problem for the rapid collapse model explored by Burkert et al. (1992).

Also, our investigation of the age for the metal-poor and metal-rich thick disk population, Sect. 1.4.2, shows that there is an overall age-metallicity relation present among the thick disk stars in the solar neighborhood. Our first results on this seem to indicate that star formation went on for at least 5 Gyr. This estimate is based on the isochrone fitting in Sect. 1.4.2 and should be taken as a conservative measure. The star formation could indeed have continued for much longer. This result seem to fully rule out a fast collapse as the formation scenario for the thick disk.

From a study of 110 edge-on disk galaxies Schwarzkopf & Dettmar (2000) concluded that thick disks are common in galaxies in mergers or in interacting environments. We think that this extra-galactic evidence is important – that thick disks are associated with mergers, and would therefore advocate a merger origin for the kinematic signature of the majority of the thick disk stars.

1.7 Conclusions

We find that the gas out of which today's thick disk stars have formed had been enriched by SNe Ia, low mass AGB stars, and that there appears to be an overall age-metallicity relation among the thick disk stars that we observe in the solar neighborhood. This has implications for the star formation history of the thick disk.

Further, we confirm previous results (e.g. Fuhrmann 1998, Prochaska et al. 2000) that the abundance trends are discrete and that the thick disk is more abundant in the α-elements than the thin disk at a given metallicity. We also find that our thick disk sample, on average, is older than our thin disk sample, 10.8 ± 4.3 Gyr and 4.9 ± 2.8 Gyr. This difference further strengthens that the thin and thick disks formed at separate time epochs.

Based on our finding that there exist stars with typical thick disk kinematics but with typical thin disk abundances and the fact that extra-galactic studies find thick disks to be associated with mergers the following, plausible, scenario for creating our observed abundance patterns is suggested: today's thick disk originate from a thin disk (which most likely was formed by rapid collapse, e.g. no gradients) that was later puffed up by a violent merger and that the star formation in that disk that is today's thick disk went on for a considerable time, perhaps as long as 5 Gyrs. After the gas had then settled into a thin disk the stars in today's thin disk were born. Some of the oldest of these stars have later experienced significant kinematic diffusion and today have kinematics typical of the thick disk but abundances typical of the thin disk.

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