# Signatures of SN Ia in the galactic thick disk. Observational evidence from alpha - elements in 67 dwarf stars in the solar neighbourhood

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*Published in:*
Astronomy & Astrophysics

*DOI:*
10.1051/0004-6361:20021661

2003

A&A 397, L1–L4 (2003)
DOI: 10.1051/0004-6361:20021661


Astronomy & Astrophysics

Letter to the Editor

# Signatures of SN Ia in the galactic thick disk★

## Observational evidence from $\alpha$-elements in 67 dwarf stars in the solar neighbourhood

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Received 23 October 2002 / Accepted 14 November 2002

**Abstract.** We present the first results of a larger study into the stellar abundances and chemical trends in long-lived dwarf stars in the solar neighbourhood that belong to (based on their kinematics) the thin and thick galactic disk, respectively. We confirm that the trends of $\alpha$-elements in the thin and thick disk are distinct (this has previously been shown for Mg by Fuhrmann 1998, but e.g. Chen et al. 2000 claimed the trends to follow smoothly upon each other). We find that the thick disk show the typical signature of contribution from SN Ia (i.e. the "knee") to the enrichment of the interstellar gas out of which the later generations of thick disk stars formed. The trend starts out as [Mg/Fe] $\sim$ 0.35 at [Fe/H] $\sim -0.7$ and continue on this level with increasing [Fe/H] until $-0.4$ dex where a decline in [Mg/Fe] starts and steadily continues down to 0 dex at solar metallicity. The same is true for the other $\alpha$-elements (e.g. Si). Using ages from the literature we find that the thick disk in the mean is older than the thin disk. Combining our results with other observational facts we suggest that the most likely formation scenario for the thick disk is, still, a violent merger event. We also suggest that there might be tentative evidence for di ffusion of orbits in todays thin disk (based on kinematics in combination with elemental abundances).

**Key words.** stars: abundances – stars: kinematics – Galaxy: abundances – Galaxy: disk – formation – Galaxy: solar neighbourhood

## 1. Introduction

Observational evidence revealed in the 1980's that the Galaxy has two disk-like components: the thin and the thick disks (Gilmore & Reid 1983). It is now also established that some, but not all, disk galaxies possess a thin and a thick disk and that the presence of a thick disk is often associated with mergers or interacting systems (Schwarzkopf & Dettmar 2000).

The stars in the thick disk have warm kinematics, $(\sigma_{\rm U}, \sigma_{\rm V}, \sigma_{\rm W}) = (67, 38, 35)$ km s$^{-1}$, and appear to all be old, e.g. Fuhrmann (1998). Its scale-height is 1000–1300 pc which is comparable to what is observed in other galaxies, Schwarzkopf & Dettmar (2000). The thin disk is more confined to the galactic plane with a scale-height of 300 pc and the stars have a cooler kinematics, $(\sigma_{\rm U}, \sigma_{\rm V}, \sigma_{\rm W}) = (35, 20, 16)$ km s$^{-1}$. Their metallicities are in the mean higher than those in the thick disk and extend up to super-solar values, Wyse & Gilmore (1995).

The chemical evolution of the thick disk, as traced by the stellar abundances in long-lived dwarf stars in the solar neighbourhood, has recently become a most active area of research, e.g. Fuhrmann (1998), Prochaska et al. (2000), Mashonkina & Gehren (2001), Chen et al. (2000), Gratton et al. (2000), and Tautvaišienė et al. (2001). However, the conclusions reached by these studies point in conflicting directions. While Gratton et al. (2000), Fuhrmann (1998), and Mashonkina & Gehren (2001) find that the star formation in the thick disk lasted less than 1 Gyr, Prochaska et al. (2000) infer a substantially longer time. Furthermore, three of the studies, Fuhrmann (1998), Chen et al. (2000), and Mashonkina & Gehren (2001), analyse the thin and thick disk stars in a differential manner. Chen et al. (2000) find that the chemical trends for the $\alpha$-elements of the thin and thick disk stars, respectively, follow smoothly upon each other, while Fuhrmann (1998) and Prochaska et al. (2000) find the trends for the thin and the thick disk to be clearly separate. All the studies agree that the thick disk is old.

Here we report our first findings of a larger study that we have initiated in order to further characterize the two disks and also to find out to what metallicities the thick disk extends. Former studies have implied that the thick disk metallicity does not extend significantly above –0.5 dex. We discuss

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★ Based on observations collected at the European Southern Observatory, La Silla, Chile, Proposals #65.L-0019(B) and 67.B-0108(B).

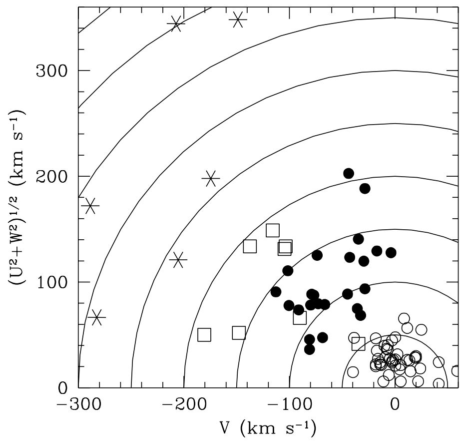


**Fig. 1.** Toomre diagram for our and Fuhrmann (1998) stars. Our thin disk stars are denoted by ∘ and thick disk stars with •. Fuhrmann's thick disk stars are shown as □ and his halo stars as ∗.

the implications of our first results from our southern sample. A northern sample is in preparation.

## 2. Our data and results

Stars were selected based on their kinematic properties. In particular we used the catalogue of more than 4000 stars compiled by Feltzing & Holmberg (2000) for their study of the moving group HR 1614. We used those velocities 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 thin or the thick disk, respectively. When selecting stars we tried to cover the metal-poor thin disk and the thick disk with even numbers of stars per metallicity bin (compare the sample selection in Edvardsson et al. 1993). 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. All stars in our sample have parallaxes with errors <5% from Hipparcos and metallicity and temperature estimates based on Strömgren photometry, Feltzing et al. (2001).

The full details of our analysis as well as abundances of iron-peak and other elements will be presented in Bensby et al. (2002, in prep.). 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. (1975) and Edvardsson et al. (1993).

Figures 2 and 3 show our abundance data. In Fig. 2 we also show the errors to let the reader appreciate the *internal* quality of the data. Our two most important findings are:

- stars that belong to distinct kinematic populations show discrete trends as traced by all the $\alpha$-elements;
- the trends for the thick disk stars show a clear signature of SN Ia contribution to the chemical enrichment (the "knee").

Other findings are more model dependent (i.e. age determinations) or are based on a small number of stars (2–5)

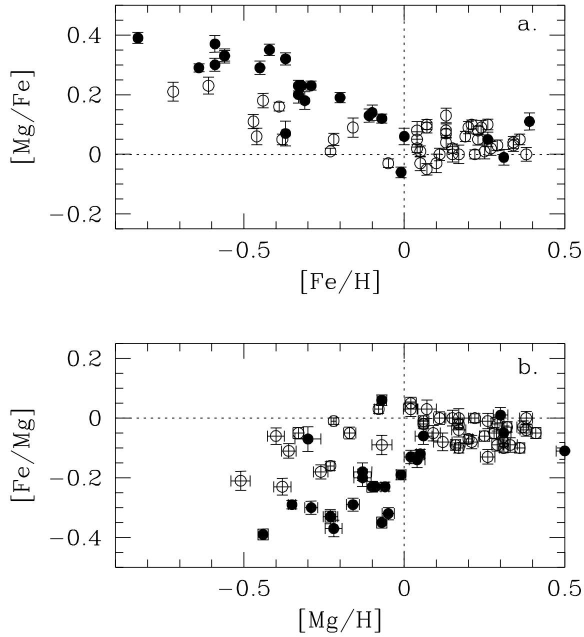


**Fig. 2.** Magnesium abundances for our program stars, error-bars give the formal error in the mean (= (line-to-line scatter) / $\sqrt{N_{\rm lines}}$). The thick disk stars are shown as • and the thin disk stars as ∘. Errors in [Fe/H] are smaller than the symbols.

and will require further investigations. The most interesting of these are:

- we find that in our sample of stars with well determined ages (see Feltzing et al. 2001) and with typical thick disk kinematics have a mean age of 12.1 ± 2.0 Gyr. For the thin disk stars we get a mean age of 6.1 ± 3.8 Gyr. Hence, the two populations do not overlap on the 1 $\sigma$ level;
- our sample contains two thin disk stars that appear very old;
- five stars with typical thick disk kinematics show typical thin disk $\alpha$-abundances.

## 3. How did the galactic thick disk form?

### *3.1. Possible scenarios*

How can thick disks form? Several scenarios have been suggested and were summarized in e.g. Gilmore et al. (1989).

- A slow, pressure supported collapse.
- A fast collapse due to increased dissipation (e.g. enhanced cooling by metals).
- Violent heating by a merger, which puffs up an originally thin disk to the velocity dispersions of today's thick disk.
- Accretion of thick disk material directly, e.g. satellites on suitable orbits.
- Enhanced kinematic diffusion of the stellar orbits in the thin disk eventually producing a thickening.

These various scenarios give definite predictions concerning the metallicity, ages, and elemental abundances of the stars. Some of the scenarios have also been modelled in detail: the fast collapse was studied by Burkert et al. (1992) and the merger scenario by e.g. Quinn et al. (1993).

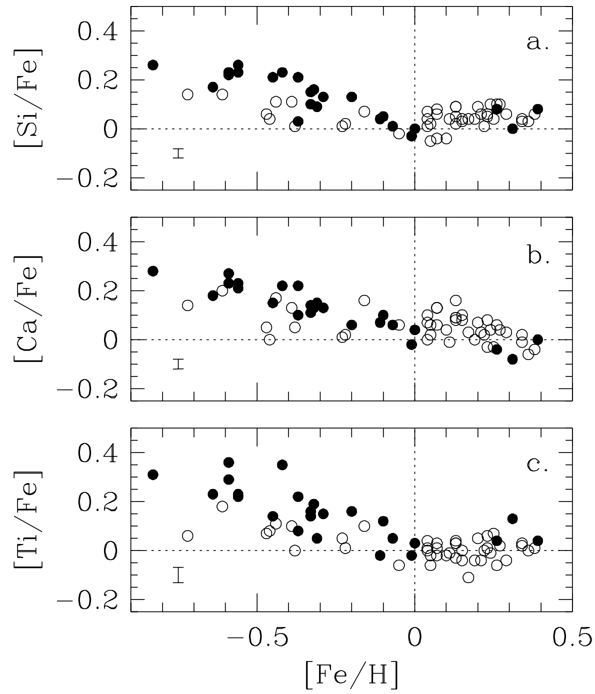


**Fig. 3.** Si, Ca, and Ti abundances for our thin disk stars, ∘, and thick disk stars, •. Typical error-bars are indicated at the bottom left and show the formal error in the mean (= (line-to-line scatter) / $\sqrt{N_{\rm lines}}$).

In the first scenario vertical abundance gradients will build up and the two disks will have overlapping age distributions. The rapid collapse, on the other hand, is fast enough (see Burkert et al. 1992 for details) that indeed there will be no time to build up gradients in the thick disk (star formation ceases after about 400 Myr in the thick disk). Further, the kinematics of the two components will be different as well as their mean metallicities.

If the thick disk is due to violent heating by a merger then the ages of the thick disk stars will all be greater than the ages of the thin disk stars. The abundance trends should, most likely, be different. Note that the models (e.g. Quinn et al. 1993) do say nothing about the formation scenario for the thin disk that is the predecessor of the thick disk. Thus there are no constraints on the chemical trends we can expect to see in the thick disk. If on the other hand material is accreted slowly over time from many smaller satellites, on suitable orbits, ages and abundances will show a mixed picture. The final mixture will depend on exactly when and how much new gas (or stars) are accreted.

Lastly, if the thick disk is due to diffusion of stellar orbits then the thick and thin disk stars come from the same stellar population. Thus they will share abundance trends as well as age distributions (although one can expect the thick disk to be mainly old).

### 3.2. Observational facts

From our differential study of the chemical trends in the thick and thin disks we find that the chemical trends in the two components are distinct, that a clear signature of SNe Ia is present in the trends for the thick disk, that the thick disk is old, and that there appear to exist stars with typical thick disk kinematics that nevertheless show typical thin disk elemental abundances.

Gilmore et al. (1995) showed that there is no discernible vertical metallicity gradient when going from 1 to 1.5 kpc above the galactic plane. At this height above the plane the thick disk dominates.

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.

### 3.3. Interpretation and discussion

Our first key result is that the two disks show distinct abundance patterns. This should rule out any model that predict that the disks should have continuous distributions, e.g. only diffusion of orbits or only 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 subsequent 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.

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 neighbourhood (modelled 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 (there are currently no observations apart from the thick disk stars themselves to constrain the star formation time in the original thin disk) 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.

We think that the 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. Obviously, some of today's thin disk stars may have got their orbits diffused and would today look like thick disk stars if we look at their orbits but like thin disk stars if we consider their elemental abundances. The number of such stars should, however, be small (Silk & Wyse 1993).

Our results mainly agree with previous studies (see list in Sect. 1), i.e. that the thin and thick disks are distinct and the thick disk is all old. However, all but one of the previous studies have found no signatures of the SN Ia in the thick disk abundances. From this a short time-scale for the formation of the thick disk has generally been derived (based on the, incorrect see above, assumption that SN Ia timescale is 1 Gyr). We argue that the reason for that previous studies of the thick disk abundances have not seen this signature is because they have deliberately excluded more metal-rich stars. The reason for this is given (e.g. Fuhrmann 1998) as the "fact" that the thick disk should not have stars much more metal-rich than –0.5 dex. We think such an ad hoc assumption is ill-founded and preferred to include stars of all metallicities. Our selection enabled us to find the presence of the SN Ia signature.

As we have performed a differential analysis of the thin and thick disk abundances our main results are robust. However, especially the time-scale for star formation in the thick disk is not determined by our abundances (remember that SN Ia can contribute on a time scale as short as 0.5 Gyr or as long as 1–2 Gyr, Matteucci 2001). 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. Especially the presence of *s*-processed elements (e.g. Ba) directly tells that AGB stars have had time to contribute to the enrichment of the interstellar medium out of which subsequent stellar populations were born. 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 their result gives a lower, and not an upper, limit to the star formation time in the thick disk. Therefore it is important to analyse *s*- and *r*-process elements of more metal-rich thick disk stars. We are currently doing this. They also found that the [Eu/Fe] started to decline at the highest metallicities in their thick disk sample. This could indeed be an indication that SN Ia started to contribute to the chemical enrichment. However, such a conjecture is based on the assumption that Eu is mainly produced in the same sites as the $\alpha$-elements. The evidence from e.g. Mg for the same stars (see Bernkopf et al. 2002, Fig. 2) does not show any down-turn at the same metallicities.

Finally, the most important test would be to obtain stellar abundances of dwarf stars that belong to the thick disk and are far away (around 1 kpc) from the galactic plane. In such a sample no kinematic bias would be present as at these heights the thick disk dominates over the thin disk and stars could be chosen without selections based on probabilities based on kinematics. Such observations, of e.g. the Gilmore et al. (1995) stars, are now possible with the UVES spectrograph on the VLT.

## 4. Summary

We find that the gas out of which today's thick disk stars have formed had been enriched by SNe Ia. This has implications for the star formation history of the thick disk. However, taking the possibility of a bursting star formation in the thick disk into account it is not impossible that such an enrichment could be achieved in less than one billion years (see e.g. Matteucci 2001). This makes our results compatible with both a merger scenario (Quinn et al. 1993) and (marginally) a fast dissipative collapse model (see Burkert et al. 1992).

Further, we confirm previous results (e.g. Fuhrmann 1998; Prochaska et al. 2000) that the thick disk is older than the thin and that the abundance trends are discrete.

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. 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. That we found an uncharacteristically large number of such stars is because we actively included stars with high metallicities and thick disk kinematics.

*Acknowledgements.* TB acknowledges a travel grant from Fysiografiska sällskapet i Lund for the first observing run at La Silla, Chile. SF acknowledges computer grants from the same society.

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