The nature of the metal-rich thick disk

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Abstract. We have traced the Galactic thick disk to its, to date, highest metallicities. Based on high-resolution spectroscopic observations of 187 F and G dwarf stars that kinematically can be associated either with the thin disk (60 stars) or with the thick disk (127 stars), we find that the thick disk stars reach at least solar metallicities, and maybe even higher. This finding is independent of the $U_{LSR}$, $V_{LSR}$ and $W_{LSR}$ velocities of the stars.

1. Introduction

The metal-rich stars of the Galactic thick disk may be an the evolutionary interface to the thin disk. The metal-rich extreme of the thick disk will help us to understand whether this transition is smooth and whether there was a hiatus in the star formation history between the two disks. Having a well-established upper metallicity limit for the thick disk is also crucial for studies of possible age-metallicity relations in the thick disk.

However, despite the efforts of several recent high-resolution spectroscopic surveys of the Galactic thick disk, it is unclear what its high-metallicity limit is. For instance, Fuhrmann (1998, 2004) suggests that the thick disk stops at $[\text{Fe}/\text{H}] \approx -0.3$; Reddy et al. (2006) find that the thick disk may not include stars with $[\text{Fe}/\text{H}] > -0.3$; and Mishenina et al. (2004) suggest, from their data, that the star formation in the thick disk stopped when the enrichment was $[\text{Fe}/\text{H}] = -0.3$. It should be noted that all of these studies actually contain stars that are more metal-rich and that have kinematic properties that could classify them as thick disk stars. However, Fuhrmann (1998, 2004) regards these stars as “transition objects” and it is unclear whether they should be treated as thin or thick disk stars, or neither. Reddy et al. (2006) find that metal-rich, potential thick disk stars mainly follow thin disk trends (Reddy et al. 2003), and Mishenina et al. (2004) claim that their metal-rich stars with hot kinematics cannot be assigned to the thick disk due to both their highly eccentric orbits, and their low Galactic vertical distribution (low $Z_{max}$). Because of this, they say that the origin of these stars should be sought elsewhere, such as e.g. in the Hercules stream (see e.g. Famaey et al. 2005). However, even if potential Hercules stream stars are excluded Soubiran & Girard (2005) find, in their compilation of high-resolution data from the literature, a considerable number of stars with thick-disk-like kinematics at high metallicities. But they also conclude that their
sample has too few metal-rich stars with thick disk kinematics to really verify their thick disk origin.

In our own studies of the thin and thick disks (Bensby et al. 2003, 2005) we do not insist on an upper metallicity limit for the thick disk, but assume that the stars we see with thick-disk–like kinematics could be members, regardless of their metallicities. And what we do find is that the kinematically hot stars that we associate with thick disk, and that have [Fe/H] > −0.3, differ significantly from the thin disk stars at the same metallicity. This applies both in terms of abundance ratios (e.g. [Mg/Fe]), as well as ages (Bensby et al. 2003, 2004, 2005; Bensby & Feltzing 2006; Feltzing et al. 2003, 2006). Also, in Bensby et al. (2007) we present a detailed abundance study of 60 F and G dwarf stars that kinematically are likely to be members of the Hercules stream. What we find is that these stars do not form a genuine population but that instead, they are likely to be a mixture of stars from the thin and thick disk populations, verifying that their kinematic properties are probably due to dynamical interactions with the Galactic bar.

As the current data on the metal-rich thick disk evidently is very sparse and since there might be indications that the stars of the Hercules stream could be a “metal-rich thick disk” it is important to observe and establish the extreme metal-rich limit of the thick disk. We have therefore carried out an extensive spectroscopic survey of metal-rich stars that kinematically can be associated with the Galactic thick disk. Special care has been applied to exclude stars that have space velocities typical of the Hercules stream.

Here, we will focus on two elements that show distinct abundance trends for the thin and thick disks: Mg (e.g., Fuhrmann 2004; Feltzing et al. 2003, 2005; Bensby et al. 2003, 2005) and Ba (e.g., Mashonkina et al. 2003; Bensby et al. 2005). Other α-elements, iron peak elements, and r- and s-process elements will be presented in an upcoming paper (Bensby et al., in prep.), wherein we also will describe the observations, data reductions, abundance analysis, and so forth.

2. Stellar sample

What characterizes the thick disk is that its stars are kinematically hot and rotationally lag behind the Local Standard of Rest (LSR) by some 50 km s$^{-1}$. In Figs. 1a and b we plot how the $U_{\text{LSR}}$, $V_{\text{LSR}}$ and $W_{\text{LSR}}$ velocities for the stars in the Nordström et al. (2004) catalogue (∼13 240 F and G dwarf stars with 3-dimensional kinematic information) are distributed as a function of metallicity. Even though there might be a slight decrease in the number of high-velocity stars as one goes to higher metallicities, there is no sharp drop-off. Instead, there seems to be a significant number of stars with both high metallicities and high velocities.

We used the kinematic method from Bensby et al. (2003, 2005) to define samples of potential thin disk and thick disk stars. This method assumes that a stellar population has a Gaussian velocity distribution and constitutes a certain fraction of the stars in the solar neighbourhood. Assuming that the solar neighbourhood is a mixture of only the thin disk ($D$), the thick disk (T$D$), the Hercules stream ($Her$), and the halo ($H$), we then calculate the probabilities for individual stars (with known space velocities) to belong to any of the popula-
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3. Observations, data reduction, abundance analysis

High-resolution \((R \approx 65\,000)\), high-quality \((S/N \geq 250)\) echelle spectra were obtained for \(\sim 200\) thick disk F and G dwarfs by TB in Jan, Apr, and Aug in 2006 with the MIKE spectrograph \((\text{Bernstein et al.}, 2003)\) on the Magellan Clay 6.5 m telescope at the Las Campanas Observatory in Chile. Here we present the results for the metal-rich part of this sample, 91 stars. Solar spectra were obtained during the runs by observing the asteroid Vesta (in Jan), the Jovian moon Ganymede (in Apr), and the asteroid Ceres (in Aug).

For the abundance analysis, we used the Uppsala MARCS stellar model atmospheres \((\text{Gustafsson et al.}, 1975, \text{Edvardsson et al.}, 1993, \text{Asplund et al.}, 1997)\).

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\(^1\)The new thick disk sample presented here only includes stars with \([\text{Fe/H}] > -0.60\). Another sample of new thick disk stars extending to lower metallicities will be presented elsewhere.
The chemical compositions of the models were scaled with metallicity relative to the standard solar abundances as given in Asplund et al. (2005), but with α-element enhancements for stars with [Fe/H] < 0. To determine the effective temperature and the microturbulence we required all Fe I lines to yield the same abundance, independent of lower excitation potential, and line strength, respectively. For the surface gravities, we utilized the accurate Hipparcos parallaxes (ESA 1997) for our stars. Final abundances were normalized on a line-by-line basis with our solar values as reference, and then averaged for each element.

4. Results

In Fig. 2, we show the resulting [Mg/Fe]−[Fe/H] and [Ba/Fe]−[Fe/H] abundance trends for all 127 stars with thick disk kinematics and for the 60 stars with thin disk kinematics. It is clear that these two groups of stars separate into distinct loci, and that those stars that can be associated with the thick disk show a flat [Mg/Fe] plateau for metallicities below [Fe/H] \( \lesssim -0.4 \), indicative of fast enrichment from massive stars. Towards higher metallicities, the [Mg/Fe] ratio for these stars declines, an indication of the delayed enrichment from low- and intermediate mass stars. Approaching solar metallicity, it also becomes harder to distinguish these stars from the kinematically cold stars of the thin disk as their [Mg/Fe] trends merge. The [Ba/Fe] ratio, on the other hand, evolves essentially in lockstep with [Fe/H] for the kinematically hot stars and is even more distinct from the thin disk [Ba/Fe] trend, especially when the two disks approach solar metallicities.
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Figure 3. [Mg/Fe] and [Ba/Fe] versus [Fe/H]. The stars with thick disk kinematics have been split into three subsamples that span different $V_{\text{LSR}}$ velocities; $V_{\text{LSR}} \leq -86$, $-86 < V_{\text{LSR}} \leq -65$, and $V_{\text{LSR}} > -65$ km s$^{-1}$, respectively. These three regions are also marked in Fig. 1d. Stars with thin and thick disk kinematics are marked by open and filled circles, respectively.

In Fig. 2, it is evident that a number of stars with thick disk kinematics have thin disk abundance ratios. In order to investigate the nature of these stars, we have divided the thick disk sample into three, equally sized subsamples with different $V_{\text{LSR}}$ velocities (see also Fig. 1d): one that has low Galactic rotation velocities ($V_{\text{LSR}} \leq -86$, Figs. 3a and d), one that has intermediate rotation velocities ($-86 < V_{\text{LSR}} \leq -65$, Figs. 3b and e), and one that has more thin-disk-like rotation velocities (but high $U_{\text{LSR}}$ and/or $W_{\text{LSR}}$) ($V_{\text{LSR}} > -65$ km s$^{-1}$, Figs. 3c and f).

Since the sub-sample with $V_{\text{LSR}} \leq -86$ km s$^{-1}$ deviates the most from the typical thin disk kinematics, it should be the sample that is the least contaminated by the thin disk, and hence the most representative for the thick disk. In Figs. 3a and d, we see that essentially all these stars are clearly distinguished from the thin disk sample and have thick disk abundance ratios. It is also clear that they indeed extend all the way up to solar metallicity. The subsample with intermediate $V_{\text{LSR}}$ velocities ($-86 < V_{\text{LSR}} \leq -65$ km s$^{-1}$) is similar to the one with $V_{\text{LSR}} \leq -86$ km s$^{-1}$ velocities, with the exception that a few stars start to fall within the thin disk abundance trends. The mixing of the populations is further increased in the $V_{\text{LSR}} > -65$ km s$^{-1}$ subsample, but still with most thick disk stars clearly differentiated from the thin disk trend. In all $V_{\text{LSR}}$ bins it is clearly demonstrated that the stars with thick disk kinematics and thick disk abundance ratios extend to at least $[\text{Fe/H}] \approx 0$.

The gradual inclusion of stars with thin disk abundance ratios as we approach higher $V_{\text{LSR}}$ velocities is probably caused by the inclusion of more and more stars from the high-velocity tail of the thin disk.

We have also investigated the effects of similar cuts in the $U_{\text{LSR}}$ and $W_{\text{LSR}}$ velocities for the thick disk sample, and the results remain.
5. Conclusion

We have used high-resolution spectroscopy to trace the Galactic thick disk to its highest metallicities. We find that the kinematically hot stars associated with the Galactic thick disk extend to at least solar metallicity, if not above. We further note that our kinematic selection criteria are not definitive, but tend to include a few stars from the high-velocity tail of the thin disk, in the thick disk sample, especially at thin-disk–like $V_{\text{LSR}}$ velocities. In an upcoming paper, we will investigate in detail improvements to the kinematic selection criteria, to determine the feasibility of weeding out the high-velocity tail of the thin disk from kinematically selected thick disk samples.

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