

# TRACING THE GALACTIC THICK DISK TO SOLAR METALLICITIES<sup>1</sup>

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## ABSTRACT

We show that the Galactic thick disk reaches at least solar metallicities and that it experienced strong chemical enrichment during a period of  $\sim 3$  Gyr, ending around 8–9 Gyr ago. This finding puts further constraints on the relation and interface between the thin and thick disks and their formation processes. Our results are based on a detailed elemental abundance analysis of 261 kinematically selected F and G dwarf stars in the solar neighborhood: 194 likely members of the thick disk and 67 likely members of the thin disk, in the range  $-1.3 \lesssim [\text{Fe}/\text{H}] \lesssim +0.4$ .

*Subject headings:* Galaxy: disk — Galaxy: evolution — Galaxy: formation — solar neighborhood — stars: abundances — stars: kinematics

## 1. INTRODUCTION

The Milky Way has since the early 1980s been known to have two disk components, a thin disk and a thick disk (Gilmore & Reid 1983). Since then, several studies, using high-resolution spectra to derive elemental abundances in disk dwarf stars, have been aimed at establishing the properties of the thick disk and to better understand its origin and role in our Galaxy (e.g., Gratton et al. 2000; Prochaska et al. 2000; Fuhrmann 2004; Mishenina et al. 2004; Reddy et al. 2006; Bensby et al. 2003, 2005). It is now known that the thick disk is a major Galactic stellar population and that its stars have hotter kinematics, have higher ages, and are chemically distinct from the stars of the thin disk. All this points to separate origins and different chemical histories for the thin and thick disks.

Recently, a lot of structure has been observed among the stars in the Galaxy. In the disk in the solar neighborhood, this is seen as various stellar streams and moving groups (e.g., Famaey et al. 2005; Helmi et al. 2006); and at larger distances, features such as, e.g., the “Field of Streams” (e.g., Belokurov et al. 2006) have been detected. So, did the thick disk form as a single entity in the initial collapse of the protogalactic cloud (e.g., Eggen et al. 1962), and/or is it a result of an ancient merger event, or is it made up of stars coming from streams and merger debris, i.e., a hierarchical origin (e.g., Abadi et al. 2003; Brook et al. 2004; Robertson et al. 2004)? A persistent question is why the Milky Way has two disk populations.

Abundance trends and the metallicity distribution function of the thick disk are vital records to its formation and evolution. However, the high metallicity limit of the thick disk remains poorly defined. For instance, Fuhrmann (2004), Mishenina et al. (2004), and Reddy et al. (2006) suggest that the thick disk extends only up to  $[\text{Fe}/\text{H}] \approx -0.3$ , because their candidate thick-disk stars at higher  $[\text{Fe}/\text{H}]$  either fall within their thin-disk abundance trends and/or have highly eccentric orbits that are near the Galactic plane. Hence, their origins should be sought elsewhere, perhaps in stellar streams like the Hercules stream (see, e.g., Famaey et al. 2005). But, even if possible

Hercules stream stars are weeded out, stars with thick-disk-like kinematics at high  $[\text{Fe}/\text{H}]$  still remain (Soubiran & Girard 2005; Bensby et al. 2007; see also Fig. 1). Furthermore, in Bensby et al. (2003, 2004, 2005) and Bensby & Feltzing (2006) we find that the thick-disk stars differ significantly from the thin-disk stars, both in terms of abundance ratios as well as stellar ages, even at  $[\text{Fe}/\text{H}]$  close to solar. However, those results are based on a small stellar sample and need confirmation.

As described, the current data for the metal-rich thick disk are confusing and ambiguous. It is therefore necessary to isolate the thick-disk abundance relations from those of other populations. Therefore, we have carried out an extensive spectroscopic survey of metal-rich stars that are kinematically associated with the Galactic thick disk. In this Letter, we discuss Ti and Ba abundance trends and combine our new results with our thin- and thick-disk results from Bensby et al. (2003, 2005). Other  $\alpha$ -,  $r$ -,  $s$ -, and iron peak elements will be discussed in an upcoming paper (T. Bensby et al. 2007, in preparation) together with the details of the kinematic selection criteria and the abundance analysis.

## 2. SELECTION OF TARGETS, OBSERVATIONS, AND ABUNDANCE ANALYSIS

The kinematic method from Bensby et al. (2003, 2005) was used to select possible thick-disk F and G dwarf stars from the Nordström et al. (2004) catalog. Briefly, the method assumes Gaussian velocity distributions for all stellar populations and that the solar neighborhood can be represented as a mixture of only the thin disk, the thick disk, the Hercules stream, and the halo. Candidate thick-disk stars are selected as those that have probabilities of belonging to the thick disk that are at least twice the probabilities of belonging to any of the other populations (and likewise for the other populations). The space velocities for the 159 new thick-disk and 10 new thin-disk stars are shown in Figures 1a–1c together with 35 thick-disk and 57 thin-disk stars from Bensby et al. (2003, 2005). Also shown, in Figure 1d, is how the thick-disk to thin-disk probability ratios ( $TD/D$ ) vary with  $[\text{Fe}/\text{H}]$ .

Echelle spectra were obtained in 2005 and 2006 with the Magellan Inamori-Kyocera Echelle (MIKE) spectrograph, on the Magellan Clay 6.5 m telescope, for 145 new thick-disk stars ( $R \approx 65,000$ ,  $S/N \gtrsim 250$ ), and in 2004 with the Ultraviolet and Visual Echelle Spectrograph (UVES), on the ESO Very Large Telescope, for 14 new thick-disk and 10 new thin-disk stars ( $R \approx 110,000$ ,  $S/N \gtrsim 250$ ).

<sup>1</sup> Based on data collected with the 6.5 m Magellan telescopes at the Las Campanas Observatory and with the Very Large Telescope at the European Southern Observatory (ESO proposal 72.B-0179).

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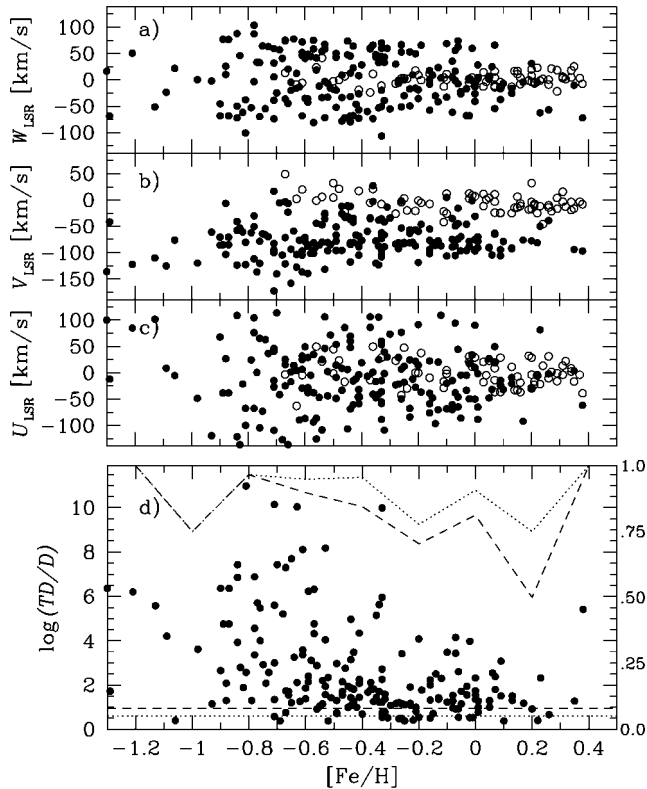


FIG. 1.—(a)–(c) Velocity-metallicity plots for the stellar sample. Thin-disk and candidate thick-disk stars are marked by open and filled circles, respectively. (d)  $TD/D$  probability ratios vs. metallicity for the thick-disk candidates. The bottom lines indicate  $TD/D = 4$  (dotted line) and  $TD/D = 9$  (dashed line). The lines on top give the corresponding fraction of stars that have  $TD/D$  larger than these ratios (scale on the right-hand side).  $[Fe/H]$  values are from our spectroscopic work.

The MARCS model stellar atmospheres (Gustafsson et al. 1975; Edvardsson et al. 1993; Asplund et al. 1997) were used in the abundance analysis. Excitation balance, and balance with line strength, of abundances from Fe I lines, were used to determine effective temperatures and the microturbulence parameter. For the surface gravities, we exploited accurate distances based on *Hipparcos* parallaxes (ESA 1997). Final abundances were normalized on a line-by-line basis with our solar values as reference and then averaged for each element.

Stellar ages were determined with the help of the Yonsei-Yale ( $Y^2$ ) isochrones (Kim et al. 2002; Demarque et al. 2004), with appropriate  $\alpha$ -enhancements, in the  $T_{\text{eff}}-M_V$  plane. Upper and lower limits on the ages were estimated from the error bars due to an uncertainty of  $\pm 70$  K in  $T_{\text{eff}}$  and the uncertainty in  $M_V$  due to the error in the parallax (see also Bensby et al. 2003).

### 3. RESULTS AND DISCUSSION

#### 3.1. Abundance Trends

Figure 2 shows the resulting  $[Ti/Fe]$  and  $[Ba/Fe]$  versus  $[Fe/H]$  trends. The stars associated with the thick disk first show a  $[Ti/Fe]$  plateau at  $[Fe/H] \lesssim -0.4$ , a signature of fast enrichment from massive stars. At higher metallicities, the thick-disk  $[Ti/Fe]$  ratio declines, indicating the delayed enrichment from Type Ia supernovae (SNe Ia). The thin disk shows an overall shallow decline in  $[Ti/Fe]$ , characteristic of slow enrichment

by *both* massive and low-mass stars. At  $[Fe/H] \approx 0$ , the trends for the two disks converge.

$[Ba/Fe]$  for the thick disk evolves almost in lockstep with  $[Fe/H]$ . As solar metallicity is approached, the thin- and thick-disk  $[Ba/Fe]$  trends diverge. At  $[Fe/H] > 0$ , it again becomes hard to differentiate the two disks.

Both  $[Ti/Fe]$  and  $[Ba/Fe]$  versus  $[Fe/H]$  demonstrate that kinematically hot stars associated with the thick disk extend to solar metallicities. However, it is also evident that there are thick-disk stars that do not follow the general thick-disk abundance trends. Instead, they chemically behave as thin-disk stars. This is at least evident in the  $[Ti/Fe]$ - $[Fe/H]$  plot as  $[Fe/H] \approx 0$  is approached.

To try to determine the nature of these ambiguous stars, we use the thin-disk sample (Figs. 2b and 2e) to visually define boundaries on  $[Ti/Fe]$  and  $[Ba/Fe]$  for the thin disk (shown as solid lines in the top four panels of Fig. 2). The number of candidate thick-disk stars that fall within the thin-disk abundance trends are shown in the bottom two panels of Figure 2. There is a steady increase with metallicity of candidate thick-disk stars that fall within the thin-disk  $[Ti/Fe]$  trend, suggesting that the contamination from the high-velocity tail of the thin disk increases with  $[Fe/H]$ . The fraction that fall within the thin-disk  $[Ba/Fe]$ - $[Fe/H]$  trend is, on the other hand, generally small, and with no apparent trend. This suggests that essentially all candidate thick-disk stars could be genuine thick-disk stars.

Due to the closeness of the thin- and thick-disk  $[Ti/Fe]$  trends at higher  $[Fe/H]$ , one can expect true members of the thick disk to fall within the thin-disk trend, and vice versa. And, since the Ba abundances are based on only three to four Ba II lines, there are larger measurement uncertainties in  $[Ba/Fe]$  than in  $[Ti/Fe]$ . Ba abundances could also be influenced by non-LTE effects, hyperfine and isotopic structure, and blends from other spectral lines (see, e.g., Mashonkina & Zhao 2006), effects that we have not accounted for. On the other hand, we present a strictly differential abundance analysis. If the above effects were severe, we would not find well-defined and distinct Ba trends for two kinematically selected samples. Hence, we believe that our Ba abundances are well determined.

#### 3.2. Age Trends

The top panel in Figure 3 shows the age distributions for the candidate thick-disk stars that follow the thick-disk  $[Ti/Fe]$  trend (as defined by the thin-disk boundary line in Fig. 2a), while the middle panel shows those that do not. Each subsample has been divided into four metallicity bins, as shown. The bottom panel shows the age distributions for the thin-disk sample.

The candidate thick-disk stars with thin-disk  $[Ti/Fe]$  ratios appear to be younger than those above the boundary. For instance, in the  $-0.35 < [Fe/H] < 0$  bin, only one out of 26 candidate thick-disk stars (4%) that have a thin-disk  $[Ti/Fe]$  ratio is older than 8 Gyr. In the same metallicity bin, 23 out of 33 stars (70%) that remain above the thin-disk  $[Ti/Fe]$  boundary are older than 8 Gyr. This duality in both ages and abundances again points to two distinct Galactic disk populations, both reaching  $[Fe/H] = 0$ .

Figure 4 shows  $[Fe/H]$  and  $[Ba/Fe]$  as a function of age, excluding stars with estimated upper and lower age limits (see § 2) that differ by more than 35%. Running medians of the ages for the thick disk, calculated in steps of 0.1 dex in  $[Fe/H]$ , using a 0.2 dex wide window in  $[Fe/H]$ , both with and without thick-disk stars that have thin-disk  $[Ti/Fe]$  ratios, are shown in Fig-

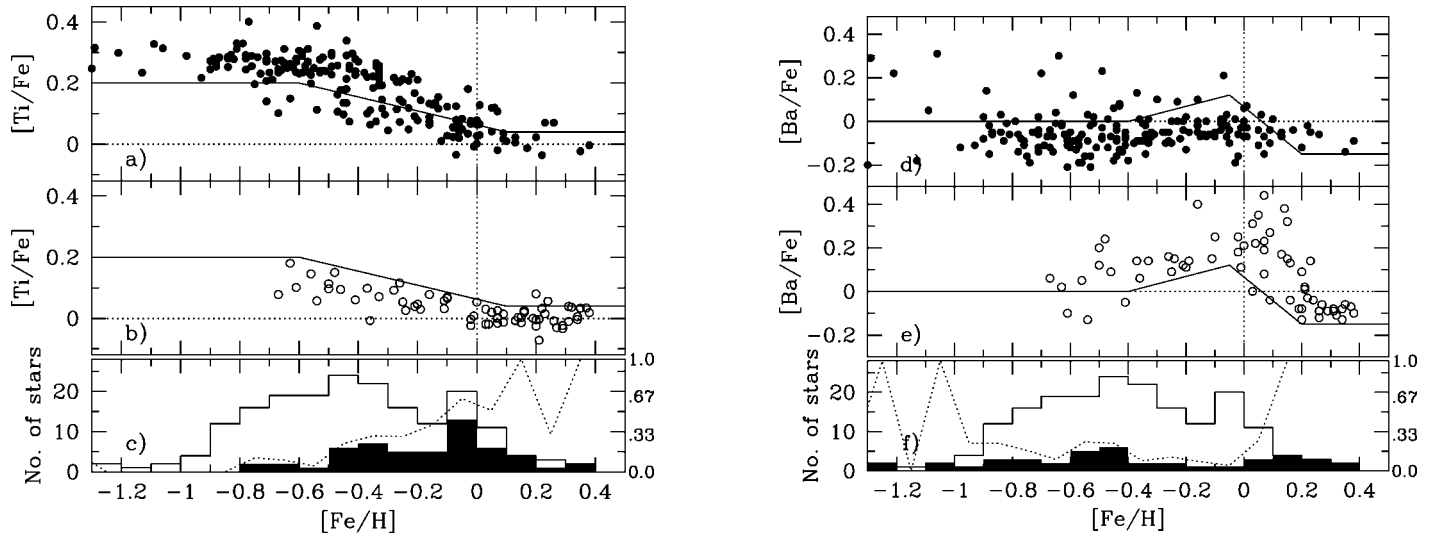


FIG. 2.—*Top four panels:*  $[\text{Ti}/\text{Fe}]$  and  $[\text{Ba}/\text{Fe}]$  vs.  $[\text{Fe}/\text{H}]$ . Thin- and thick-disk stars are marked by open and filled circles, respectively. Solid lines mark the boundary for the thin sample. *Bottom panels:* Distribution of all 195 thick-disk stars (*white histograms*) and the thick-disk stars that fall within the thin-disk abundance trends (*black histograms*). The dotted line in the bottom panels shows the fraction (scale on the right-hand side) of thick-disk stars in each bin that fall within the thin-disk abundance trends.

ure 4a. For  $[\text{Fe}/\text{H}] \leq -0.8$ , median ages are typically  $\sim 12$  Gyr. The median age at higher  $[\text{Fe}/\text{H}]$  depends on whether thick-disk candidates that have thin-disk  $[\text{Ti}/\text{Fe}]$  ratios are included or not. As many of the stars that fall below the  $[\text{Ti}/\text{Fe}]$  boundary have ages comparable to the stars that do not, it is likely that the actual relation is intermediate to the solid and dashed lines. The age of the thick disk at solar metallicities is then  $\sim 9$  Gyr, i.e., it takes the thick disk  $\sim 3$  Gyr to reach  $[\text{Fe}/\text{H}] \approx 0$ .

### 3.3. The Metal-rich End of the Galactic Thick Disk

Our kinematically hot stars appear to come from an old stellar population, with ages of 8–12 Gyr, that extend at least to

$[\text{Fe}/\text{H}] \approx 0$ . Not only is this population old, but also its stars have kinematic properties typical of the Galactic thick disk and chemical properties similar to what is found in the Galactic thick disk. Furthermore, preliminary results show that the abundance and age trends do not vary with either of the  $U_{\text{LSR}}$ ,  $V_{\text{LSR}}$ , and  $W_{\text{LSR}}$  velocities (T. Bensby et al. 2007, in preparation; but see also Bensby et al. 2006). Therefore, this appears to be manifest evidence that this stellar population indeed is the Galactic thick disk. That the thick disk really reaches all the way up solar metallicities verifies the existence of the “knee” present in most thick-disk  $[\alpha/\text{Fe}]$  trends. Hence, the thick disk formed stars for at least 3 Gyr and experienced strong enrichment, from both SNe II and SNe Ia, during this period, ending  $\sim 8$ –9 Gyr ago.

### 3.4. The Relation between the Thin and Thick Disks

In our sample, the most metal-poor stars with thin-disk kinematics have metallicities of  $[\text{Fe}/\text{H}] \approx -0.7$  and ages around 5 Gyr. Hence, these stars are considerably younger than the most metal-rich thick-disk stars at  $[\text{Fe}/\text{H}] \approx 0$  whose ages are 8–9 Gyr. At supersolar metallicities, the thin-disk stars appear to have ages comparable to those of the most metal-poor ones, i.e.,  $\sim 5$  Gyr, suggesting that they formed at the same time! This phenomenon could be explained by the infall of gas into the Galaxy, which initially was poorly mixed with the remains of the old metal-rich gas. The first stars of the thin disk could then be metal-rich ( $\geq 0.3$ ), metal-poor ( $\leq -0.5$ ), or, depending on the degree of mixing of the gas, of any metallicity in the range  $-0.7 \leq [\text{Fe}/\text{H}] \leq +0.4$ . This scenario may explain why there is no well-defined age-metallicity relation in the solar neighborhood (e.g., Edvardsson et al. 1993; Feltzing et al. 2001; Haywood 2006). However, we caution that age uncertainties can be large and that the increase in dispersion of the metallicity with stellar age, for nearby stars, partly could be due to migration of stellar orbits (e.g., Haywood 2006; Wielen et al. 1996).

Figure 4b shows  $[\text{Ba}/\text{Fe}]$  versus stellar age. The two disks appear to follow smoothly in time, and there also appears to

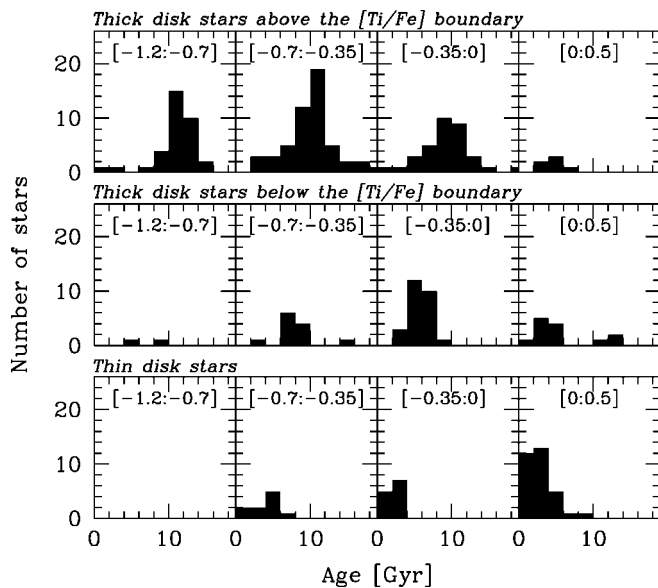


FIG. 3.—The top and middle panels show age distributions for thick-disk stars that fall above and below the  $[\text{Ti}/\text{Fe}]$  boundary, respectively. The bottom panel shows the thin-disk distribution. All age distributions are divided into four metallicity bins, as indicated in the square brackets at the top of each panel.

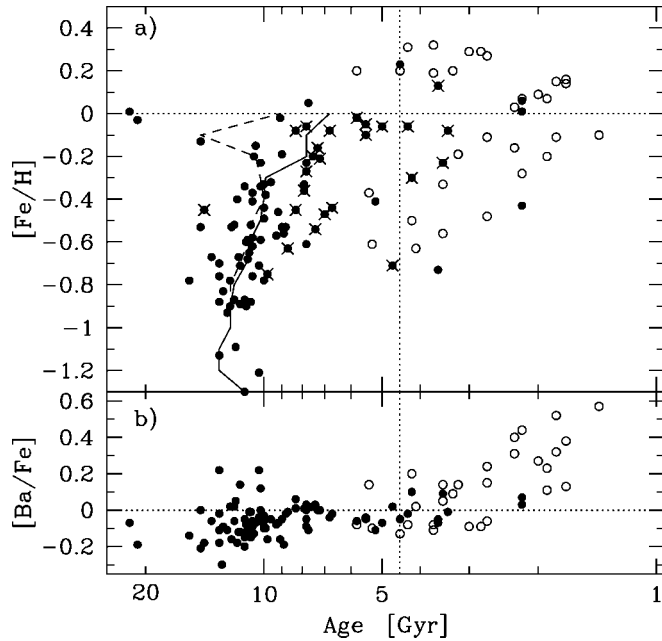


FIG. 4.—[Fe/H] and [Ba/Fe] vs. age. Stars for which the upper and lower age estimates differ by at most 35% are included. Thin- and thick-disk stars are marked by open and filled circles, respectively. The solid line shows the running median ages (see text) for the thick-disk stars, and the dashed line when excluding thick-disk stars that have thin-disk [Ti/Fe] values (*crosses*). The vertical, dotted line is the age of the Sun (4.5 Gyr).

be a quiescent period of 1–2 Gyr when almost no stars were formed, some 6–7 Gyr ago. However, our thin-disk stellar sample has by no means been selected to probe its oldest parts. Hence, a possible hiatus, and the fact that there are (a few) stars that have ages in between the two disks, should be investigated with a sample targeted for the oldest thin disk.

Figure 4b also helps us to further understand the origin and evolution of Ba in the Galactic disks. The “bump” in the thin-disk [Ba/Fe]-[Fe/H] trend (Fig. 2e) is no longer seen. As the most metal-rich thin-disk stars evidently are not the youngest ones, there is now instead a steady increase in [Ba/Fe] toward younger ages. The first, flat portion of the [Ba/Fe] trend is consistent with being due to the *r*-process. As the *s*-process becomes significant (due to asymptotic giant branch stars), [Ba/Fe] will rise. The position of the Sun is consistent with an origin during the early times of the thin disk, when Ba enrichment was mainly *r*-process dominated but started to give way to being *s*-process dominated. However, we caution that the solar Ba composition is thought to be ~80% *s*-process and ~20% *r*-process (e.g., Arlandini et al. 1999).

#### 4. SUMMARY

We have presented clear evidence that the Galactic thick disk reaches at least solar metallicities and thus that it experienced strong chemical enrichment during an early period ending some 8–9 Gyr ago.

The plot of [Ba/Fe] versus time, instead of [Fe/H], offers a more straightforward interpretation of the evolution of Ba at high metallicities.

We find that even the most metal-rich stars of the thick disk are older than the thin-disk population, with a possible hiatus in the star formation between these two populations. We are continuing to investigate these relationships with a stellar sample designed to target the oldest stars of the thin disk.

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