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A FIRST CONSTRAINT ON THE THICK DISK SCALE LENGTH: DIFFERENTIAL RADIAL ABUNDANCES IN K GIANTS AT GALACTOCENTRIC RADII 4, 8, AND 12 kpc*

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ABSTRACT

Based on high-resolution spectra obtained with the MIKE spectrograph on the Magellan telescopes, we present detailed elemental abundances for 20 red giant stars in the outer Galactic disk, located at Galactocentric distances between 9 and 13 kpc. The outer disk sample is complemented with samples of red giants from the inner Galactic disk and the solar neighborhood, analyzed using identical methods. For Galactocentric distances beyond 10 kpc, we only find chemical patterns associated with the local thin disk, even for stars far above the Galactic plane. Our results show that the relative densities of the thick and thin disks are dramatically different from the solar neighborhood, and we therefore suggest that the radial scale length of the thick disk is much shorter than that of the thin disk. We make a first estimate of the thick disk scale length of $L_{\rm thick} = 2.0$ kpc, assuming $L_{\rm thin} = 3.8$ kpc for the thin disk. We suggest that radial migration may explain the lack of radial age, metallicity, and abundance gradients in the thick disk, possibly also explaining the link between the thick disk and the metal-poor bulge.

Key words: Galaxy: abundances – Galaxy: disk – Galaxy: evolution – Galaxy: formation – Galaxy: stellar content – stars: abundances

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Thick disks in external galaxies were discovered by Burstein (1979) when the vertical light profiles of a few edge-on spiral galaxies could not be fitted by single exponentials. Similarly, the Galactic thick disk was first detected when star count data toward the south Galactic pole could not be fitted with one power law, instead requiring two (Gilmore & Reid 1983). As there is no a priori law that says that the vertical star counts in spiral galaxies must fit single power laws, this finding was necessary but not sufficient to define the thin and thick disks as unique entities. The duality of the Galactic disk has been further seen in its kinematic and chemical properties: the thick disk lags the local standard of rest (LSR) by ≈40–50 km s^{-1}, the thick disk is more metal-poor than the thin disk (e.g., Gilmore et al. 1995; Wyse & Gilmore 1995), the thick disk is older than the thin disk (e.g., Fuhrmann 2008; Bensby et al. 2007), and the thick disk is α-enhanced, at a given metallicity, with respect to the thin disk (e.g., Fuhrmann 2008; Bensby et al. 2003, 2004, 2005; Reddy et al. 2006).

The above studies are based on stellar samples within the solar cylinder, i.e., at Galactocentric distances ($R_{\rm G}$) around 8 kpc. The inner and outer regions of the Galactic disk are far less studied. Actually, the inner disk is one of the least studied regions of the Milky Way due to the high interstellar extinction and contamination by background bulge stars. Apart from a few studies of bright hot OB stars (e.g., Daflon & Cunha 2004) and Cepheids (e.g., Luck et al. 2006) that trace the young disk stellar population, the only available data on the abundance structure of the inner Galactic disk are from Bensby et al. (2010a) who studied 44 red giants located 3–7 kpc from the Galactic center, and found evidence for a similar duality as seen in the solar neighborhood.

The outer disk is comparatively well studied, especially using red giants in open clusters (e.g., Yong et al. 2005; Jacobson et al. 2011, and references therein), and to very large $R_{\rm G}$ (>20 kpc; Carraro et al. 2007). Also OB stars (e.g., Daflon & Cunha 2004; Daflon et al. 2004) and Cepheids (e.g., Andrievsky et al. 2004; Yong et al. 2006) have been observed in the outer disk. Carney et al. (2005) observed three outer disk field red giants, which turned out to have abundance ratios similar to those in outer disk open clusters. These studies show an abundance gradient which is very steep inside $R_{\rm G} \approx 10$ kpc. For distances greater than $R_{\rm G} > 10$ kpc it is less steep, or possibly even flat, converging on metallicity around $[\mathrm{Fe/H}] \approx -0.3$ (see also Twarog et al. 1997 and the compilation by Cescutti et al. 2007). Open clusters, OB stars, and Cepheids all trace the young stellar population of the disk, and it is therefore unclear whether the outer disk shows a similar duality as observed in the solar neighborhood and in the inner disk.

This Letter extends the study on red giants in the inner disk by Bensby et al. (2010a) to include red giants in the outer disk. Detailed elemental abundances are presented for 20 red giant stars, located at $R_{\rm G}$ between 9 and 13 kpc, and 0.5 to 2 kpc from the Galactic plane. They have been analyzed using the exact same methods as used in the study of inner disk giants by Bensby et al. (2010a) and in the study of red giants in the bulge and the nearby thin and thick disks by Alves-Brito et al. (2010). This allows for a truly differential comparison, free from systematic offsets and uncertainties between the different stellar samples.

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* This Letter includes data gathered with the 6.5 m Magellan Telescopes located at the Las Campanas Observatory, Chile.

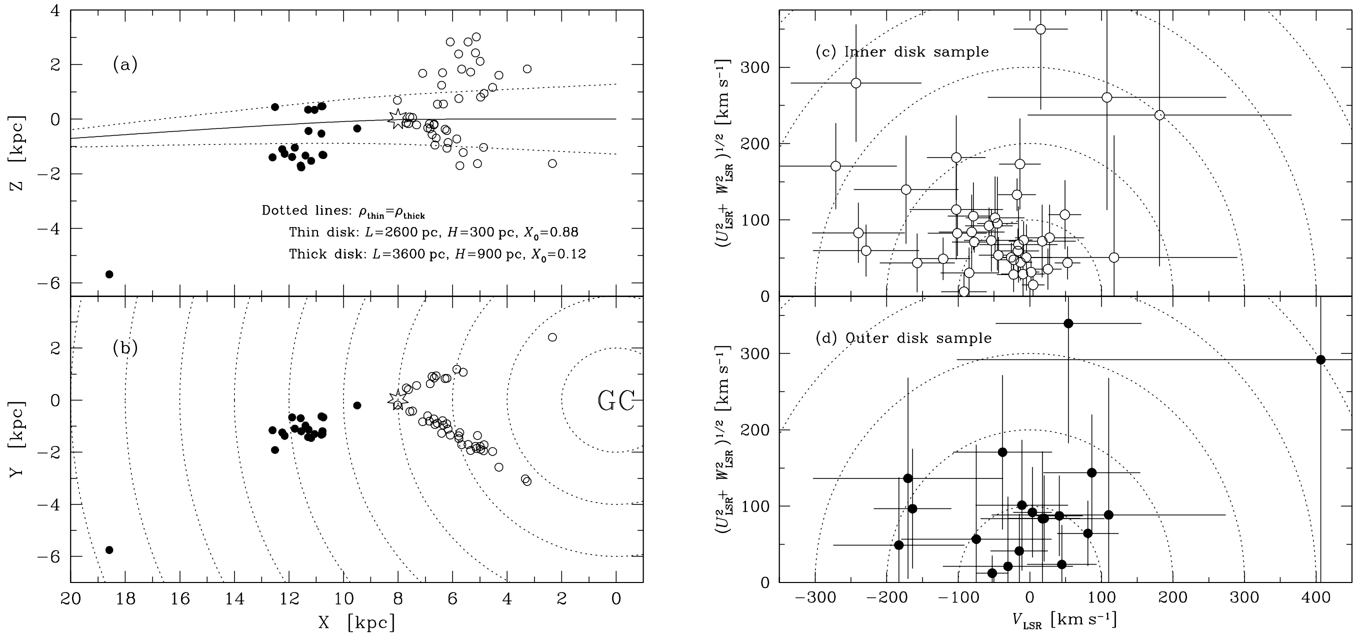

Figure 1. (a) and (b) show the locations of the stars in Galactic X, Y, and Z coordinates. Outer disk stars are marked by filled circles and the inner disk stars from Bensby et al. (2010a) by open circles. Dotted lines in (a) represent the distances above and below the plane where the thin and thick disk stellar densities are equal, given the scale lengths, scale heights, and normalizations for the thin and thick disks given by Jurić et al. (2008). The warp of the disk as given by Momany et al. (2006) has been included. (c) and (d) show Toomre diagrams for the inner and outer disk samples, respectively.

Table 1
Stellar Parameters, Kinematics, and Abundances

Object	l	b	d	V_r	U_{LSR}	V_{LSR}	W_{LSR}	T_{eff}	log g	[Fe/H]	[Mg/Fe]	[Si/Fe]	[Ti/Fe]
04342992 + 0306013	192.7	−28.4	3.6	40.8	−21	−31	−4	4100	1.2	−0.52	0.11	0.01	0.02
14053981 + 1304554	329.4	45.9	2.3	18.2	−82	−79	65	4200	1.9	−0.45	0.25	0.27	0.29

Notes. The table also includes data for the 44 inner disk giants from Bensby et al. (2010a).

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

2. SAMPLE SELECTION, OBSERVATIONS, AND ANALYSIS

2.1. *Methods*

Twenty red giants in the outer disk, selected from the Two Micron All Sky Survey catalog, were observed with the MIKE spectrograph (Bernstein et al. 2003) on the Magellan telescopes in 2007 November. Sample selection, instrumental setup, data reduction, abundance analysis, determination of distances, space velocities, and orbital parameters were done in exactly the same way as for the 44 inner disk red giants in Bensby et al. (2010a), where we direct the reader for the details. Table 1 gives the stellar parameters, kinematics, and elemental abundances for the 20 outer disk giants *and* the 44 inner disk giants from Bensby et al. (2010a).

2.2. *Stellar Parameters*

The 20 outer disk stars have effective temperatures and surface gravities in the ranges 3900 K $<$ T$_{eff}$ $<$ 5100 K and 0.9 $<$ log g $<$ 3.2, respectively, which is typical for K red giant stars, and similar to the 44 inner disk giants from Bensby et al. (2010a).

2.3. *Distances and Kinematics*

Nineteen of the 20 outer disk giants have R_G between 11 and 13 kpc, and one is very far away at $R_G \approx 19$ kpc (see Figures 1(a) and (b)). Given the warp of the Galactic disk from Momany et al. (2006), and the scale heights, scale lengths, and normalizations of the thin and thick disks in the solar neighborhood from Jurić et al. (2008), the dotted lines in Figure 1(a) show the distance from the plane where the densities of thin and thick disk stars are equal. At $X = 5$ kpc they are equal at 1.04 kpc, at $X = 8$ kpc at 0.90 kpc, and at $X = 11$ kpc at 0.75 kpc. Our inner and outer disk samples have been observed without prior knowledge of kinematics and/or metallicities. Therefore, if the thin and thick disks exist at these locations in the Galaxy and follow the assumed scale heights and scale lengths, the stars in the inner and outer disk samples should consist of *both* thin disk stars *and* thick disk stars. Actually, Figure 1(a) indicates that the outer disk sample should contain 13 thick disk stars and seven thin disk stars, while the inner disk sample should contain 21 thick disk stars and 23 thin disk stars.

Based on kinematics, stars with total space velocities less than about 85 km s^{-1} are generally associated with the thin disk, while stars with higher velocities are associated with the thick disk (e.g., Fuhrmann 2004). These criteria are based on

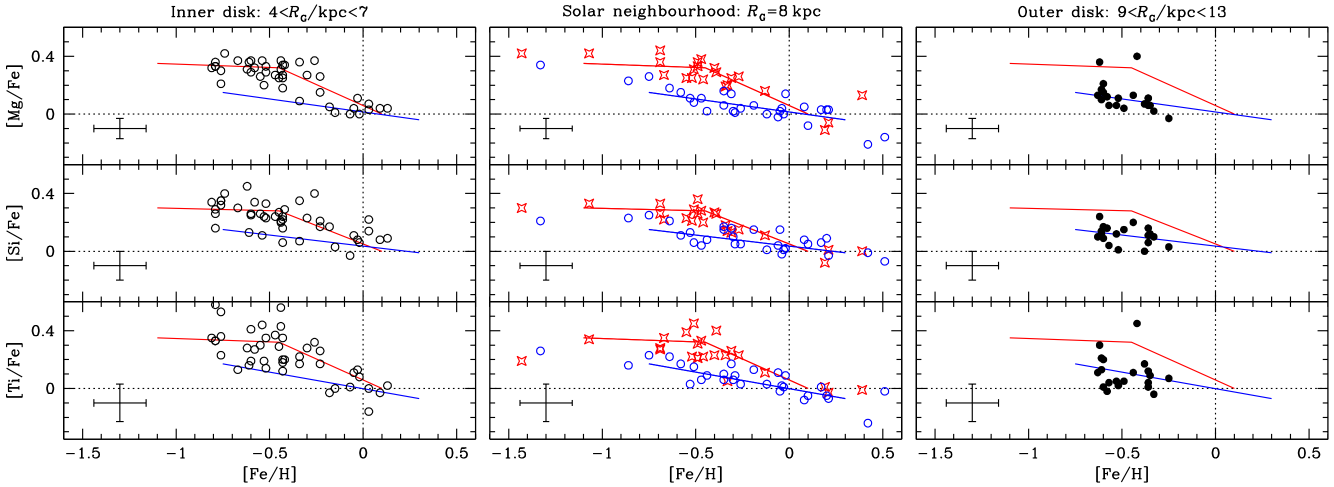

Figure 2. Abundance trends for the α-elements Mg, Si, and Ti. The left panel shows the 44 inner disk red giants from Bensby et al. (2010a), the center panel shows the solar neighborhood thin and thick disk stars (blue circles and red stars, respectively) by Alves-Brito et al. (2010). The right panel shows the 20 new outer disk red giants. The red and blue lines in the abundance plots are fiducial lines based on the solar neighborhood abundance trends.

(A color version of this figure is available in the online journal.)

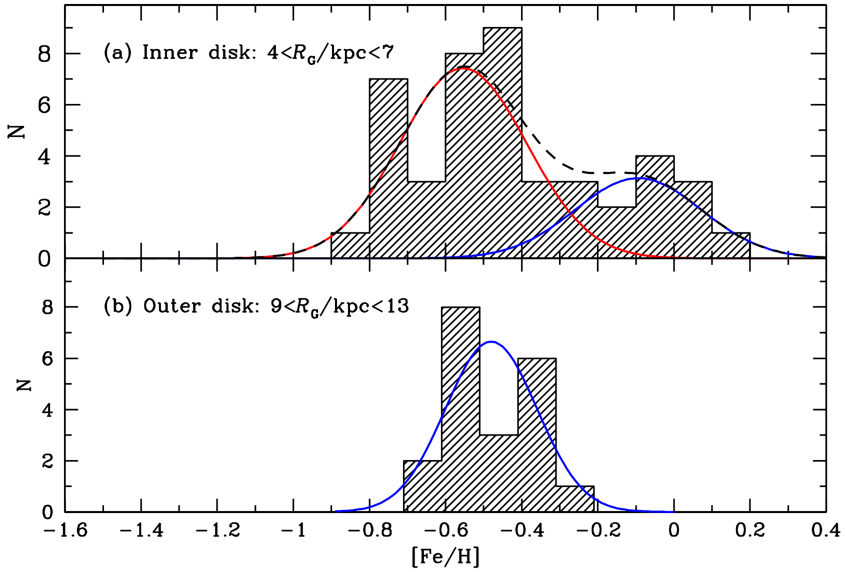

Figure 3. Metallicity distribution for the inner disk sample show two Gaussians, one based on stars with $[\mathrm{Mg/Fe}] \geqslant 0.2$ that has $\langle[\mathrm{Fe/H}]\rangle = -0.55 \pm 0.17$ (red curve) and one for stars with $[\mathrm{Mg/Fe}] \geqslant 0.2$ that has $\langle[\mathrm{Fe/H}]\rangle = -0.09 \pm 0.17$ (blue curve). The Gaussian shown for the outer disk sample has $\langle[\mathrm{Fe/H}]\rangle = -0.48 \pm 0.12$.

(A color version of this figure is available in the online journal.)

solar neighborhood data, and if they are to be applied to stellar samples farther away, such as our inner and outer disk giant samples, one assumes that the properties of the thin and thick disks in the solar neighborhood are also valid there. However, as showed by Bensby & Feltzing (2010), it should be cautioned that kinematical criteria can introduce significant mixing of the two populations as stars from the high-velocity tail of the thin disk are classified as thick disk stars (especially at high metallicities), and stars from the low-velocity tail of the thick disk as thin disk stars (especially at low metallicities). Despite the large errors in the proper motions from Zacharias et al. (2010), which results in very large errors in the space velocities, we show in Figures 1(c) and (d) the Toomre diagrams for the inner and outer disk stars, and it is clear that they sample both the thin and the thick disk velocity spaces.

3. ABUNDANCE RESULTS

The abundance results for the outer disk giants are shown in Figure 2, where they are compared to the Bensby et al. (2010a) inner disk red giant sample, and the Alves-Brito et al. (2010) sample of thin and thick disk red giants in the solar neighborhood, and in Figure 3 where we show the metallicity distribution functions (MDFs). We stress again that all stars were analyzed using exactly the same methods.

A first thing to notice is that the MDFs for the inner and outer disk samples are very different. The inner disk MDF has a large spread ($\langle[\mathrm{Fe/H}]\rangle_{\mathrm{inner}} = -0.42 \pm 0.27$) and suggests a bi-modal distribution, while the outer disk MDF has a much smaller spread $\langle[\mathrm{Fe/H}]\rangle_{\mathrm{outer}} = -0.48 \pm 0.12$. Within the limited sample, the outer disk MDF is entirely consistent with a single value. The dispersion can be attributed solely to measurement

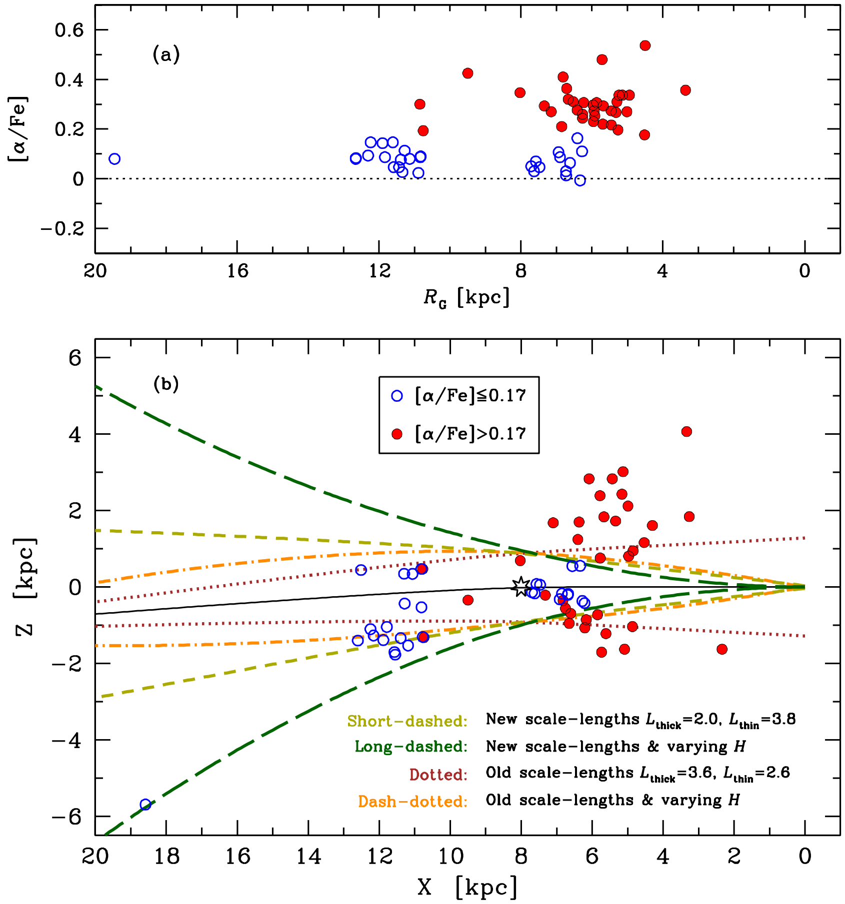

Figure 4. (a) [α/Fe] vs. $R_{\rm G}$. (b) The inner and outer disk samples in the Galactic X–Z coordinate system. The curves show loci where the two populations have equal stellar density, for different assumed scale lengths L and scale heights H (see Section 4.1 for further details). In both (a) and (b), stars with [α/Fe] > 0.17 are marked by filled red circles, while stars with [α/Fe] $\leqslant 0.17$ are marked by open blue circles.

(A color version of this figure is available in the online journal.)

uncertainties. Dividing the inner disk sample into two, one with stars that have [Mg/Fe] $\geqslant 0.2$ (thick disk) and one with stars that have [Mg/Fe] < 0.2 (thin disk), results in two metallicity distributions with $\langle$[Fe/H]$\rangle = -0.55 \pm 0.17$ and $\langle$[Fe/H]$\rangle = -0.09 \pm 0.17$, respectively.

Regarding the outer disk, almost all stars have abundance ratios similar to what is seen in the nearby thin disk. This result is surprising because, based on the kinematics and the distances from the plane, a majority of the 20 stars should be thick disk stars. But only one, or maybe two, of the outer disk giants show thick disk abundance patterns.

The abundance trends of the inner disk sample appear to contain stars with abundance patterns consistent with the nearby thin and thick disks. In Bensby et al. (2010a) we concluded that it is possible that a thin–thick disk duality, similar to the one seen in the solar neighborhood, is also present in the inner Galactic disk.

Figure 4(a) shows the [α/Fe] abundance ratio[6] versus $R_{\rm G}$. All outer disk giants with distances beyond 11 kpc have [α/Fe] ≈ 0.05, while the inner disk giants have a larger spread and reaches [α/Fe] ≈ 0.4. The one or two stars in the outer disk sample with elevated [α/Fe] ratios are among the outer disk sample stars with smallest $R_{\rm G}$. There appears to be a sudden step in the [α/Fe] abundance ratios at $R_{\rm G} \approx 11$ kpc, beyond which no stars with α-enhancements typical of the nearby thick disk stars can be seen.

4. DISCUSSION

The apparent lack of stars with thick disk chemistry in the outer disk, even for stars high above the Galactic plane, yields at least two possible interpretations: (1) the thick disk abundance gradient is steeper than that of the thin disk, yielding degenerate [α/Fe] ratios around 12 kpc; or more speculatively, (2) the thick disk's radial scale length is much shorter than that of the thin disk, so that most of our outer disk sample is dominated by thin disk stars. In this section, we explore the second possibility.

4.1. A Short Scale Length for the Thick Disk?

A shorter scale length for the thick disk means that the thick disk will be more dominant in the inner disk, and the thin disk will be more dominant in the outer disk. This is illustrated by the short-dashed line in Figure 4(b) where the thick disk scale length has been changed so that a majority of the outer disk stars are within the limits where the thick disk stars starts to dominate. Jurić et al. (2008) found that the scale lengths for the thin and thick disks were anti-correlated, so when decreasing the thick disk scale length from 3.6 kpc to 2.0 kpc, we simultaneously increased thin disk scale length from 2.6 kpc to 3.8 kpc.

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[6] α is defined here as the mean of Mg, Si, and Ti.

In Figure 4(b), stars with $[\alpha/\mathrm{Fe}] > 0.17$ are marked by red solid circles and stars with $[\alpha/\mathrm{Fe}] \leqslant 0.17$ by open blue circles. With the new scale lengths, we see that also for the inner disk sample, the new scale lengths appear to better match chemistry versus vertical distance from the Galactic plane.

So far, we have kept the vertical scale heights fixed for the two disks, assuming that they do not vary with R_G. This is most likely not the case. For instance, in a minor merger formation scenario for the thick disk, Qu et al. (2011) show that the thick disk scale height increases linearly with R_G/L. The orange dash-dotted lines in Figure 4(b) show how the equal density loci change when keeping the old scale lengths from Jurić et al. (2008) *and* varying the scale heights linearly with R_G/L. The vertical distance from the plane where the thin disk dominates will only slightly increase with R_G, and further out it will decrease again. Also shown in Figure 4(b) is the case when adopting the *new* scale lengths *and* varying the scale heights with R_G (green long-dashed lines). The vertical distances from the plane where the thin disk dominates will now increase even more than it did when the scale heights were fixed. Even the very distant giant star at $R_G \approx 20$ kpc is now within the thin disk dominated region. In all cases, a constant has been multiplied to the scale height functions so that the normalizations and scale lengths in the solar neighborhood are reproduced.

4.2. *Metallicity Gradients in the Disks*

The average metallicity of the thin disk in the solar neighborhood is $\langle[\mathrm{Fe/H}]\rangle = -0.06 \pm 0.22$ (Casagrande et al. 2011). Assuming that the outer disk sample is purely thin disk, the average metallicity of the thin disk at $R_G \approx 11$ kpc is $\langle[\mathrm{Fe/H}]\rangle = -0.48 \pm 0.12$. This implies that there is a strong abundance gradient in the thin disk, going from $R_G = 8$ kpc to $R_G = 11$ kpc, fully consistent with other studies of young stellar tracers (see, e.g., Cescutti et al. 2007).

The solar neighborhood thick disk MDF peaks at $[\mathrm{Fe/H}] = -0.60$ (e.g., Lee et al. 2011). The metal-poor part of our bimodal inner disk is likely associated with the thick disk (see Figure 2) and has an average metallicity of $[\mathrm{Fe/H}] = -0.55$. These inner thick disk stars are on average located at $R_G \approx 6$ kpc. Over this 2 kpc radial baseline, the thick disk seems to lack an abundance/metallicity gradient all together.

Looking further into the inner regions of the Galaxy, recent studies of microlensed dwarf stars in the bulge have shown that the bulge MDF is bi-modal with one peak at $[\mathrm{Fe/H}] \approx -0.6$ and another at $[\mathrm{Fe/H}] \approx +0.3$. In between the peaks there is a void where no microlensed dwarf stars have been found (Bensby et al. 2010b, 2011). The stars in the metal-poor bulge show the same abundance trends, same average metallicities, and have the same age structure as the thick disk. These similarities have been seen in studies of giants as well (e.g., Alves-Brito et al. 2010). Although currently it is only possible to state that the thick disk and metal-poor bulge have experienced similar chemical histories, this intriguing similarity may suggest that they are indeed the same population. As the metal-poor bulge population peaks at $\langle[\mathrm{Fe/H}]\rangle = -0.60$ (Bensby et al. 2011), which is identical to the value for the thick disk in the solar neighborhood, this would mean that the thick disk within the solar radius, all the way into the Galactic center, is completely homogeneous: no metallicity gradients, abundance gradients, or age gradients are seen.

Could it be possible that radial migration is the cause for the lack of gradients in the thick disk? Radial migration describes processes that cause the orbit of a star to change such that information on their formation radius is lost; this was first discussed by Sellwood & Binney (2002). Radial migration has certainly surfaced as an important mechanism in the modeling of disk galaxies (e.g., Roškar et al. 2008a, 2008b; Schönrich & Binney 2009a, 2009b; Loebman et al. 2010). As radial migration of stellar orbits is a relatively slow process, it should have affected old stellar populations more than young populations. This might suggest that the metal-poor bulge and the thick disk were formed at the same time and that the thick disk's radial metallicity gradient (if any was present) has been washed out over time, while in the younger thin disk the gradient is still present.

We note that the probability of radial migration steeply decreases with increasing radial distance (see, e.g., Figure 4 of Bird et al. 2011) for an isolated galaxy. However, mergers can make the migration probability much flatter, so a wide variety of results should be possible just by introducing mergers as an additional parameter. Assuming no significant mergers, migration should be much more efficient in the inner Galaxy, and the contribution from the inner disk will become progressively less important for the outer disk. We further note that Lépine et al. (2011) emphasize that it is rather easy to mix material from the inner regions up to about the solar distance, but that at around 8.5 kpc from the Galactic center there is a circular region void of material, the corotation gap (e.g., Amôres et al. 2009), and that mixing between the inner ($R_G < 8.5$ kpc) and outer ($R_G > 9$ kpc) parts would be more difficult.

Furthermore, studies of radial color and stellar mass density profiles for external late-type spiral galaxies have revealed that as many as 90% have light profiles that can be classified as broken exponentials (e.g., Bakos et al. 2008). Their interpretation is that the break is due to a radial change in the stellar population, rather than being a drop in the distribution of mass. Also, resolved population studies from the *Hubble Space Telescope* show radial breaks in the stellar populations (e.g., de Jong et al. 2007). This might be similar to what we see in the Milky Way, an inner disk region (coupled to the bulge/thick disk stellar populations) which has been more affected by radial migration than the thin disk stellar population.

5. CONCLUSIONS

We have presented a detailed elemental abundance analysis of 20 giants in the outer Galactic disk. Our results unambiguously show a lack of stars with thick disk chemical patterns in the outer disk, even for stars very far from the Galactic plane. While this does not necessarily imply anything about the structure of the two disk populations, we propose that this reflects a major difference in the scale lengths between these components, and that the thick disk scale length is significantly shorter than that of the thin disk. We make a first estimate and find that a scale length of $L_{\mathrm{thick}} = 2.0$ kpc for the thick disk and $L_{\mathrm{thin}} = 3.8$ kpc for the thin disk are good matches to our observations.

There is increasing evidence of a connection between the metal-poor bulge and the thick disk, regarding their abundance patterns, MDFs, ages, and a flat radial abundance gradient in the thick disk (Meléndez et al. 2008; Alves-Brito et al. 2010; Bensby et al. 2010b, 2011; this work). Stellar radial migration could plausibly explain the lack of radial gradients in the thick disk over the Galaxy's history. All evidence indicates a link between both populations, pointing to a shared origin.

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