

THE EMERGENCE OF THE THICK DISK IN A COLD DARK MATTER UNIVERSE

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ABSTRACT

The disk galaxy simulated using our chemodynamic galaxy formation code, GCD+, is shown to have a thick-disk component. This is evidenced by the velocity dispersion versus age relation for solar neighborhood stars, which clearly shows an abrupt increase in velocity dispersion at a look-back time of approximately 8 Gyr, and is in excellent agreement with observation. These thick-disk stars are formed from gas that is accreted to the galaxy during a chaotic period of hierarchical clustering at high redshift. This formation scenario is shown to be consistent with observations of both the Milky Way and extragalactic thick disks.

Subject headings: galaxies: evolution — galaxies: formation — Galaxy: disk

1. INTRODUCTION

Since its existence was detected through star counts by Gilmore & Reid (1983), the thick disk has become established as a component of the Milky Way that is distinct from the thin disk. It is hoped that the old age of the stars associated with the thick disk of the Milky Way means that it will serve as a fossil record of the formation processes of the early parts of Galactic evolution.

Several large surveys have been undertaken to constrain the properties of the Milky Way's thick disk. The local number density of thick-disk stars is about 6%–13% of that of the thin disk (e.g., Chen et al. 2001); the thick disk has a scale height of 0.6–1 kpc (e.g., Phleps et al. 1999; Ojha 2001; Chen et al. 2001), about 3 times larger than the thin disk, and a scale length of ~ 3 kpc (e.g., Robin et al. 1996; Ojha 2001) compared with a thin-disk scale length of ~ 4.5 kpc (e.g., Habing 1988). Its stars are old, almost exclusively older than 12 Gyr (e.g., Gilmore & Wyse 1985; Edvardsson et al. 1993; Fuhrmann 1998). Thick-disk stars have a wide range of metallicity, $-2.2 \leq [\text{Fe}/\text{H}] \leq -0.5$ (Chiba & Beers 2000), although the metal-weak ($[\text{Fe}/\text{H}] < -1.0$) tail of the distribution contributes only $\sim 1\%$ of the thick disk (Martin & Morrison 1998) and may be a different population than that in the canonical thick disk (Beers et al. 2002). We also note that Feltzing et al. (2003, hereafter FBL03) find that the thick-disk metallicity distribution extends to metallicities higher than $[\text{Fe}/\text{H}] = -0.5$. The metallicity distribution peaks at $[\text{Fe}/\text{H}] \sim -0.6$ (Gilmore & Wyse 1985; Wyse & Gilmore 1995; Chiba & Beers 2000). Thick-disk stars are also characterized by their warm kinematics and a rotation that lags the thin disk, e.g., Strömberg (1987) find $(\sigma_U, \sigma_V, \sigma_W) = (65, 54, 38)$ km s $^{-1}$ and $V_{\text{lag}} \sim 40$ km s $^{-1}$.

There is mounting evidence that chemical trends in the thick- and thin-disk stars are different (Fuhrmann 1998; Prochaska et al. 2000; Tautaišienė et al. 2001; Schröder & Pagel 2003; Mashonkina et al. 2003, hereafter MGTB03; Reddy et al. 2003; FBL03; but see also Chen et al. 2000 for a conflicting view). A major diagnostic coming from such

different chemical trends between thin disks and thick disks is the different α -element-to-iron abundance ratios, indicating different formation timescales. The enhanced α -element abundances compared to iron that are observed in thick-disk stars indicate a short formation timescale in which enrichment is dominated by Type II supernovae (SNe II). Although FBL03 found evidence of SNe Ia enrichment in the most metal-rich of the thick-disk stars, their values for $[\alpha/\text{Fe}]$ are systematically higher than thin-disk stars with the same $[\text{Fe}/\text{H}]$. Fuhrmann (1998), Gratton et al. (2000), and Mashonkina & Gehren (2001) conclude that star formation in the thick disk lasted less than 1 Gyr, while correlations of various chemical elements in thick-disk stars lead MGTB03 to estimate this timescale to be ~ 0.5 Gyr. MGTB03 also conclude that the homogeneity of abundances of thick-disk stars indicates that it formed from gas that was well mixed, a conclusion that is consistent with the results of Nissen & Schuster (1997), Fuhrmann (1998), and Gratton et al. (2000).

Over the past decade or more, N -body cosmological simulations have been successful in reproducing many properties of disk galaxies. Recently, using a new implementation of SNe feedback, Brook et al. (2004) successfully simulated a realistic disk galaxy that has its stellar mass dominated by a young stellar disk component, surrounded by a less massive, old, metal-poor stellar halo. In this paper we examine this simulated disk galaxy for evidence of a thick-disk component, looking for clues as to the origins of this component within the hierarchical galaxy formation of a cold dark matter (CDM) context.

In § 2, we give details of our N -body chemodynamic evolution code, GCD+, and the semicosmological galaxy formation model that we employ. Initial conditions are chosen that lead to the formation of a late-type galaxy, whose properties are presented in § 3. Further study of our simulated galaxy provides evidence for the existence of a distinct thick-disk population, similar to that of the Milky Way. This allows us to trace the major thick-disk formation epoch and propose a thick-disk formation scenario. In § 4 we compare our scenario with other theories of thick-disk formation and discuss how

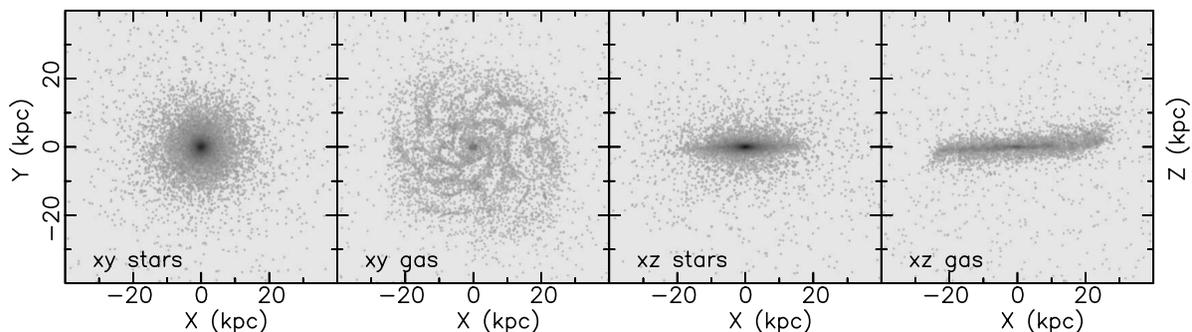


FIG. 1.—The $z = 0$ density plots for stars and gas in both the XY (face-on) and XZ (edge-on) planes. The galaxy is dominated by a stellar disk and a large gaseous thin disk, still undergoing star formation, has also formed.

current observational data can be used to distinguish these theories.

2. THE CODE AND MODEL

This paper analyzes data from the simulated late-type galaxy of the adiabatic feedback model from Brook et al. (2004). We briefly review some features of the code and model. Our galactic chemodynamic evolution code, GCD+, self-consistently models the effects of gravity, gasdynamics, radiative cooling, and star formation. We include SNe Ia and SNe II feedback and trace the lifetimes of individual stars, which enables us to monitor the chemical enrichment history of our simulated galaxies. Details of GCD+ can be found in Kawata & Gibson (2003).

We assume that 10^{51} ergs is fed back as thermal energy from each SN. The energy is smoothed over the nearest neighboring gas particles using the smoothed particle hydrodynamics (SPH) kernel. This feedback scheme is known to be inefficient (Katz 1992). To address this problem, gas within the SPH smoothing kernel of SNe II explosions is prevented from cooling, creating an adiabatic phase for gas heated by such SNe. This is similar to a model presented in Thacker & Couchman (2000).

The semicosmological version of GCD+ used here is based on the galaxy formation model of Katz & Gunn (1991). The initial condition is an isolated sphere of dark matter and gas. This top-hat overdensity has an amplitude δ_i at initial redshift z_i , which is approximately related to the collapse redshift z_c by $z_c = 0.36\delta_i(1 + z_i) - 1$ (e.g., Padmanabhan 1993). We set $z_c = 1.8$, which determines δ_i at $z_i = 40$. Small-scale density fluctuations are superimposed on the sphere, parameterized by σ_8 . These perturbations are the seeds for local collapse and subsequent star formation. Solid-body rotation corresponding to a spin parameter λ is imparted to the initial sphere to incorporate the effects of longer wavelength fluctuations. A large value of λ is chosen along with initial conditions in which no major merger occurs in late epochs ($z < 1$), in order to ensure that a disk galaxy is formed. For the flat CDM model described here, the relevant parameters include $\Omega_0 = 1$, baryon fraction $\Omega_b = 0.1$, $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, total mass $5 \times 10^{11} M_\odot$, star formation efficiency $c_* = 0.05$, spin parameter $\lambda = 0.0675$, and $\sigma_8 = 0.5$. We employed 38,911 dark matter and 38,911 gas/star particles, making the resolution of this study comparable to other recent studies of disk galaxy formation (e.g., Abadi et al. 2003).

3. PROPERTIES OF FINAL GALAXIES

Figure 1 shows a density plot of the final stellar and gas populations of the simulated galaxy, both face-on and edge-

on. The stellar mass is dominated by a young disk component. A large gaseous thin disk, still undergoing star formation, has also formed. The stellar population of the low-mass stellar halo component is old and metal-poor. The star formation history is shown in Figure 2, which plots look-back time against the star formation rate (SFR). The SFR peaks ~ 9 Gyr ago. The SFR then declines over the next 4–5 Gyr but is reasonably steady over the last ~ 5 Gyr.

We are interested here in the thick-disk component. In observations of the Milky Way, the peculiar velocity of stars is a useful diagnostic to distinguish thick-disk stars from thin-disk stars. For observed solar neighborhood stars, it is well established that there is a relationship between velocity dispersion and age. Figure 3 shows the observed relation as gray symbols, with error bars, as read from Figure 3 of Quillen & Garnett (2001), who use the data of Edvardsson et al. (1993). The velocity dispersions plateau between the ages of ~ 10 and 2 Gyr; these stars belong to the old thin disk. A slight decrease in dispersion is apparent for young star particles, less than ~ 2 Gyr old. Notably, the velocity dispersions increase abruptly, approximately doubling, ~ 10 Gyr ago. These older stars belong to the thick disk.¹ In Figure 3 we use plus symbols to plot the relation between the three components of the velocity dispersion and the stellar age for solar neighborhood star particles in our simulation. The solar neighborhood is defined as the annulus $4 \text{ kpc} < R_{XY} < 12 \text{ kpc}$ and $|Z| < 1 \text{ kpc}$.

¹ We note that a more recent study by Nordström et al. (2004) revisits this relation, and finds that the thin-disk stars do show a slight increase of velocity dispersion with age, but stars older than ~ 10 Gyr were excluded from their study.

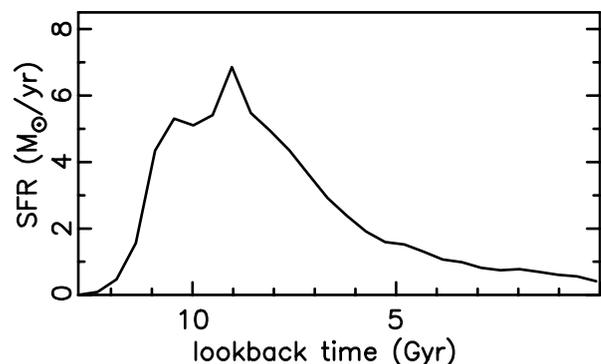


FIG. 2.—Global star formation rate (SFR) as a function of look-back time for our simulation. A peak of star formation is evident ~ 9 Gyr ago.

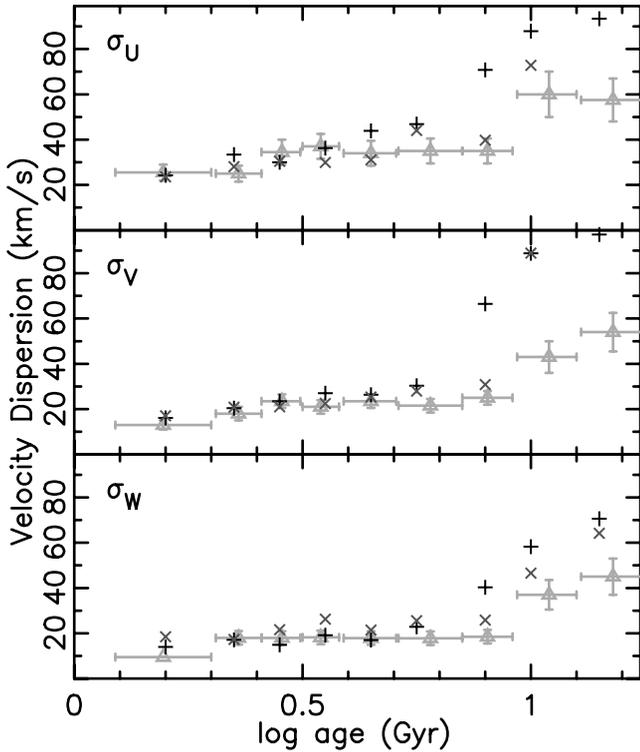


FIG. 3.—Age-velocity dispersion relation in the U , V and W direction for solar neighborhood simulation star particles, plotted as plus signs. An abrupt increase in the velocity dispersion is apparent at look-back time of ~ 8 Gyr. Also plotted (triangles with error bars) is the velocity dispersion-age relation derived by Quillen & Garnett (2001, Fig. 3), for the observed solar neighborhood stars from the sample of Edvardsson et al. (1993). Results of a disk galaxy simulation with $z_c = 2.2$ are plotted as crosses. In this simulation, the major merging epoch was earlier, and the abrupt increase in velocity dispersion pushed back in time to ~ 10 Gyr.

The abrupt increase in velocity dispersion, associated with the thick disk, is unmistakably reproduced in our simulation.

Interestingly, the timing of the abrupt increase in velocity dispersion in our simulations corresponds to the end of the peak of the SFR (Fig. 2). This motivated us to explore the main processes that were taking place during this epoch of the peak SFR, when stars of ages more than 8 Gyr were

forming rapidly. This epoch appears to be associated with thick-disk formation. Figure 4 displays the evolution of the stellar (*top panels*) and gaseous (*bottom panels*) density distribution of the simulated galaxy during this epoch, between 9.5 and 8.3 Gyr ago. This epoch is characterized by a series of merger events and is by far the most chaotic period during the galaxy’s evolution. At the beginning of this epoch, ~ 10 Gyr ago, at least four protogalaxies of significant mass exist. These building blocks are gas-rich, with a combined gas mass of $\sim 2.4 \times 10^{10} M_\odot$, compared with a stellar mass of $\sim 7.0 \times 10^9 M_\odot$. By ~ 8 Gyr ago, a single central galaxy emerges. The flattened nature of this central galaxy is apparent in Figure 4 (*bottom right*), yet this disk is significantly thick. The thin disk forms in the quiescent period of the remaining 8 Gyr.

There is an offset in the timescales of the thick-disk formation between the simulation and observation, with the observational and simulated galaxy’s abrupt increase in velocity dispersion occurring around 10 and 8 Gyr ago, respectively. To further investigate this offset, we examine a simulation that evolves to a disk galaxy in which the collapse redshift, $z_c = 2.2$, was earlier than that for the model examined so far in this paper. This galaxy less resembles the Milky Way in that it has a large bulge component, yet it also has a prominent disk. The major merging epoch of this galaxy is earlier than that for our previous model, and this is reflected in the relation between velocity dispersion and age represented by crosses in Figure 3, where the abrupt increase in velocity dispersion has been pushed back in time to ~ 10 Gyr. The implication is that the offset is a result of the merging histories of the different galaxies.

We consider some further properties of the stars that are formed in the chaotic period of galaxy formation that we have identified with thick-disk formation and make comparisons with stars that form in the later quiescent epoch. We remind the reader that our simulated galaxy is not a model of the Milky Way but rather a Milky Way-like late-type galaxy; precise quantitative agreement in any of the properties examined would not be expected. Star particles with age < 7 ($8.5 < \text{age} < 10.5$) Gyr are referred to as thin (thick) disk stars. A (somewhat arbitrary) cut in rotational velocity ($V_{\text{rot}} < 50 \text{ km s}^{-1}$) is then made, and all stars with $V_{\text{rot}} > 50 \text{ km s}^{-1}$ are defined as halo stars. This cut does not affect the thin disk but identifies around 10% of the stars that formed during the epoch

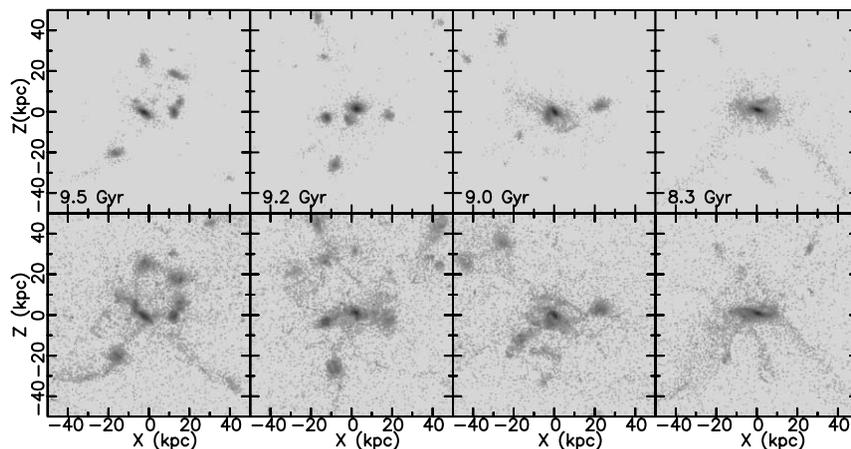


FIG. 4.—Density plot of the evolution of the galaxy’s stars (*top panels*) and gas (*bottom panels*) during the era in which the break in the velocity dispersion plot indicates that thick-disk stars are formed. This epoch is characterized by multiple mergers of gas-rich building blocks, resulting in the formation of a central galaxy.

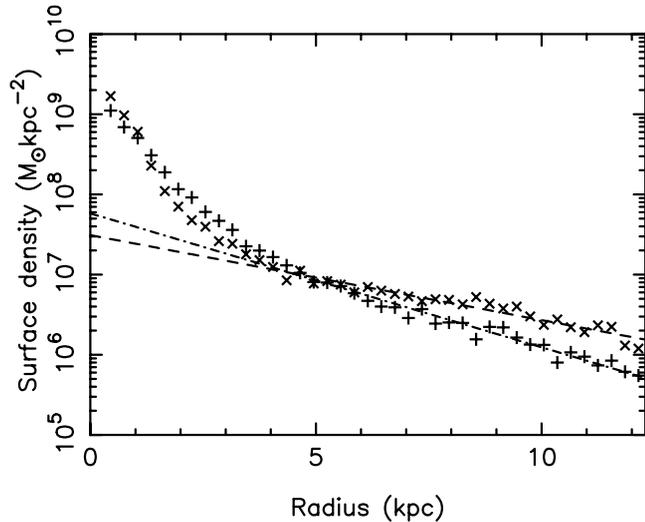


FIG. 5.—Surface density profile of the thin and thick disks, shown as crosses and plus signs, respectively. Star particles with ages < 7 Gyr are called thin-disk stars, while star particles with ages $8.5 < \text{age} < 10.5$ Gyr are thick-disk stars, with a velocity cut taken at $V_{\text{rot}} > 50$ km s $^{-1}$, which eliminates halo star contamination. The profiles are well approximated by exponentials, with fits between $4 < R < 12$ kpc shown as dashed and dot-dashed lines for thin- and thick-disk components, indicating scale lengths of 4.1 and 2.6 kpc, respectively.

of thick-disk star formation as halo stars. The simplicity of our assignment of stars to thin and thick disks on the basis of age allows us to link properties of the different component's stars to processes occurring at the different epochs at which they form.

Figure 5 shows the surface-density distributions of the thin- and thick-disk components of our simulated galaxy. Both components are well approximated by exponential profiles within the region $4 < R < 12$ kpc, with scale lengths of 4.1 and 2.6 kpc for the thin and thick disks, respectively. Figure 6 shows the vertical density distributions of the thin- and thick-disk components, averaged over the region $4 < R < 12$ kpc. The exponential profiles of these plots indicate scale heights of 0.5 and 1.3 kpc for the thin and thick disk, respectively. The rotation curves of the thin and thick

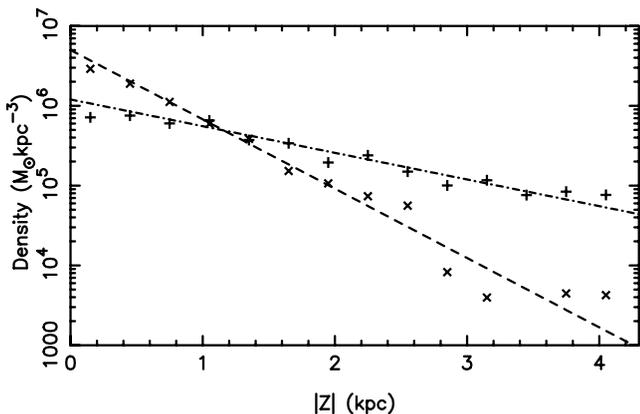


FIG. 6.—Vertical density profile of the thin and thick disks, averaged over the region $4 < R < 12$ kpc, shown as crosses and plus signs, respectively. The profiles are well approximated by exponentials, with fits shown as dashed and dot-dashed lines for thin- and thick-disk components, indicating scale heights of 0.5 and 1.3 kpc, respectively.

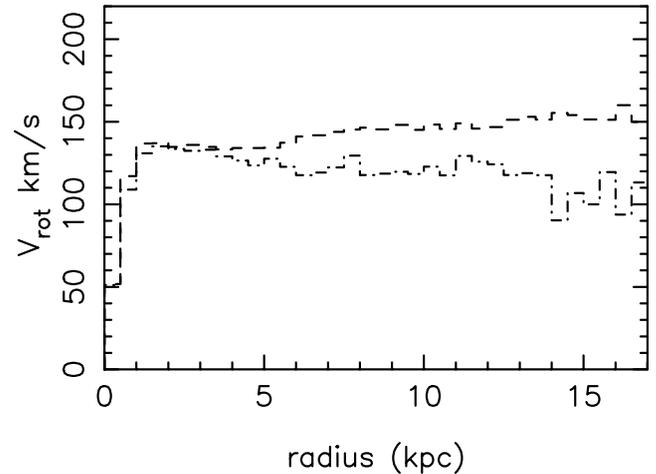


FIG. 7.—Rotation curve for the thin-disk (*dashed line*) and thick-disk (*dot-dashed line*) components. The thick disk lags the thin disk by approximately 20 km s $^{-1}$ in the solar neighborhood.

components are shown as dashed and dot-dashed lines in Figure 7, respectively. The thick disk lags the thin disk by approximately 20 km s $^{-1}$ in the solar neighborhood. The implication of these plots is to confirm that our simulated galaxy has both a thin- and thick-disk component and that these components are qualitatively similar to those of the Milky Way (see § 1).

The metallicity distribution functions of solar neighborhood stars, defined as above, are shown in Figure 8. Thin-disk stars (*dashed line*) peak at $[\text{Fe}/\text{H}] \sim -0.1$. Thick-disk stars (*dot-dashed line*) have greater spread in metallicity than thin-disk stars, despite their tighter age spread, and peak at $[\text{Fe}/\text{H}] \sim -0.3$. This makes our thick-disk component more metal-rich than that of the Milky Way. In Brook et al. (2004) a link was made between the mass ratios of the components of simulated galaxies and the metallicities of those components. The stellar halo of our simulated galaxy is both more massive and more metal-rich than that observed for the Milky Way (Brook et al. 2004). This would naturally be associated with the gas-rich building blocks associated with thick-disk formation in our simulation being more metal enriched than those of the

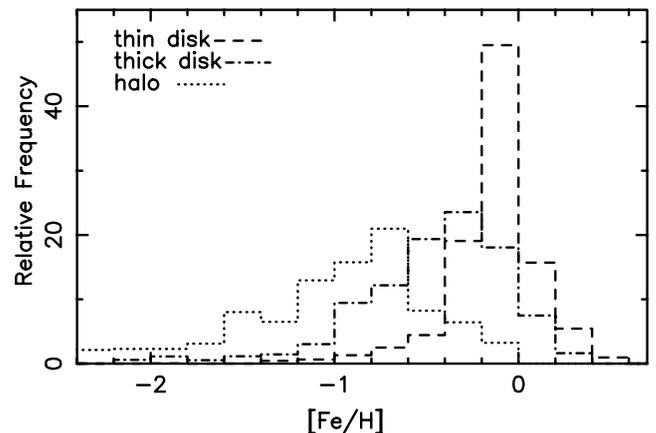


FIG. 8.—Metallicity distribution function of solar neighborhood stars, defined as $4 < R < 12$ kpc and $|Z| < 1$ kpc, for thin-disk stars (*dashed line*), thick-disk stars (*dot-dashed line*), and halo stars (defined as stars with $V_{\text{rot}} < 50$ km s $^{-1}$ with no age cut, *dotted line*).

Milky Way. Halo stars (*dotted line*) are defined as stars with $V_{\text{rot}} < 50 \text{ km s}^{-1}$ and peak at $[\text{Fe}/\text{H}] \sim -0.8$,² with a large tail toward lower metallicities. As noted, the higher metallicity of the halo stars compared to the Milky Way, which has a peak at $[\text{Fe}/\text{H}] \sim -1.5$, is due to the stellar halo of the simulated galaxy being more massive than the Milky Way's halo. This massive stellar halo, resulting in larger than observed contamination of the solar neighborhood by halo stars, may also explain why the abrupt increase in velocity dispersion seen in Figure 3 is larger for our simulated galaxy than for the Milky Way.

4. DISCUSSION

We have shown that properties of solar neighborhood star particles from our simulated disk galaxy are intimately related to processes that can be associated with different epochs. The majority of solar neighborhood stars that form during a chaotic merging period, between 10.5 and 8.5 Gyr ago in our simulation, are characteristically thick-disk stars. A small portion of stars born in this time are halo stars. Solar neighborhood stars that form in the more quiescent period over the past ~ 8 Gyr are characteristically thin-disk stars.

Our results indicate that the thick disk is created in an epoch of multiple mergers of gas-rich building blocks, during which a central galaxy is formed. The stars that form during this merging period, when a high SFR is triggered (Fig. 2), are the dominant source of thick-disk stars. A significant fraction of the gas accreted to the central galaxy during this epoch carries the angular momentum of the protogalactic cloud, imparted by the large-scale structure of the universe. This angular momentum results in the rotation and flattening of the central galaxy that is formed. Yet this epoch is characterized by violent interactions, and the forming gas disk can be described as dynamically hot, resulting in the high velocity dispersion of the forming stars in the disk. The result is the formation of a thick disk. Infalling gas after this multiple merger epoch settles smoothly to a thin disk.

Several formation scenarios for the thick disk were presented by Gilmore et al. (1989): (1) a slow, pressure-supported collapse that follows the formation of halo Population II stars (Larson 1976); (2) violent dynamical heating of the early thin disk by satellite accretion (Quinn et al. 1993) or violent relaxation of the Galactic potential (Jones & Wyse 1983); (3) direct accretion of thick-disk material (Statler 1988; Bekki & Chiba 2000; Abadi et al. 2003); (4) enhanced kinematic diffusion of the thin-disk stellar orbits (Norris 1987); and (5) a rapid dissipational collapse triggered by high metallicity (Wyse & Gilmore 1988). To unravel which of these processes was the major driver of thick-disk formation, information on the metallicity, ages, and chemical abundances of thick-disk stars can be compared with the predictions that the various scenarios make.

Lack of a vertical metallicity gradient in the thick disk (Gilmore et al. 1995), as well as the lack of a large, intermediate-age thick-disk population, seems to rule out the slow collapse of scenario 1. The lack of overlapping age distributions between thick- and thin-disk stars, as well as the discontinuity in their chemical abundances, argues against the enhanced kinematic diffusion scenario 4. Further evidence against such

a scenario is the size of the discontinuity in velocity dispersion, which appears to be too great to be explained by the known heating mechanisms, i.e., local gravitational perturbations in the thin disk, such as giant molecular clouds (Spitzer & Schwarzschild 1953) or transient spiral structure (Barbanis & Woltjer 1967; Carlberg & Sellwood 1985). Freeman (1991) suggested that these disk-heating mechanisms saturated or became inefficient at $\sigma \sim 30 \text{ km s}^{-1}$. Lack of correlation between the scale lengths of the thick- and thin-disk components of disk galaxies observed in Dalcanton & Bernstein (2002, hereafter DB02) also contradicts scenario 4 for thick-disk formation in other galaxies. If the thick disk were made up primarily of material accreted slowly over time from many smaller satellites on suitable orbits, as in scenario 3, then the metallicity of the stars would be too low to explain the observed peak metallicity of the thick disk. The well-known metallicity-mass relation of galaxies would require accretion of massive satellites ($>10^{10} M_{\odot}$), which would destroy the thin disk, in order to obtain metallicities of $[\text{Fe}/\text{H}] \sim -0.6$, unless the accreted satellites were gas-rich and the accretion process induced a significant self-enrichment (Bekki & Chiba 2002). In addition, recent high-resolution spectroscopic observations of individual stars in dwarf spheroidal (dSphs) find solar α -element-to-iron abundance ratios (e.g., Shetrone et al. 2001, 2003) that differ significantly from observed $[\alpha/\text{Fe}]$ and $[\text{Fe}/\text{H}]$ in the thick disk. This indicates that the accretion of systems similar to dSphs is not the dominant source of thick-disk stars. As noted by Wyse (2004), all the thick-disk formation scenarios allow the possibility of a portion of the thick-disk stars to have originated directly from accretion.

The heating of the disk early in its violent evolution, as in scenario 2, is well supported by Galactic observations (Quillen & Garnett 2001; Wyse 2000; Gilmore et al. 2002; Freeman & Bland-Hawthorn 2002; FBL03). This scenario is consistent with the observed abrupt increase in velocity dispersions, the distinct chemical properties of the two disk components, and the homogeneity of thick-disk abundances. We contend that our scenario of thick-disk formation during the epoch of multiple mergers of gas-rich building blocks is consistent with scenario 2, and hence with these observations of the Milky Way's thick disk. We note that scenario 2 suggests two possible heating mechanisms. In the first mechanism of scenario 2 a thin disk forms and is heated by an accretion event. Evidence that the thick disk has had a more intense star formation history than the thin disk (e.g., Bensby et al. 2003; MGTB03) would seem to favor the mechanism we propose over this "puffed up" thin disk, although the latter mechanism is not inconsistent with a rapid thick-disk formation timescale (e.g., FBL03). Our simulations more closely resemble the mechanism of Jones & Wyse (1983), in which a thick disk forms during a violent relaxation of the galactic potential, prior to the formation of the thin disk. We note also that the in situ formation of the thick disk in our scenario leads to efficient self-enrichment. Our scenario also incorporates features of scenario 3, but rather than accreting stars into the thick disk directly, our scenario envisages star formation being triggered by accretion of gas-rich building blocks during a chaotic merging epoch at *high redshift*. The increased cooling due to metals, as mentioned in scenario 5, helps ensure a rapid SFR in the thick disk. Thus, although we are proposing our thick-disk formation scenario as "new," it shares features with previously proposed scenarios.

² The metallicity distribution functions derived using the same simulated galaxy in Brook et al. (2004) use different methods to define halo and disk stars, resulting in slightly different metallicity distribution functions.

We have underway a program to examine a statistically significant number of simulated disk galaxies similar to those examined here, with varying masses, angular momenta, and merging histories. This will help determine whether the properties of our thick disk-like component depend on the adopted model parameters and specific merger histories. We hope to predict the expected frequency of thick disks and to characterize thick-disk properties such as age, metallicity, and color of the stellar populations.

The formation of the thick disk in the manner we have outlined is a natural consequence of the early, violent merging epoch of the CDM universe, indicating that thick disks would be a widespread component of disk galaxies. Recent, deep observations of a sample of 47 nearby edge-on galaxies by

DB02 indicate that thick disks are almost ubiquitous around disk galaxies. A lack of correlation between thick- and thin-disk scale lengths, as found by DB02, is also explained by our formation scenario. Confirmation of these findings would strengthen the case for our thick-disk formation mechanism.

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