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Geometrical Structures of Chemically Decomposed Thick and Thin Disk Populations

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Abstract. We summarize the thick and thin disk formation commonly seen in cosmological N-body simulations. As suggested in Brook et al. (2004), a hierarchical clustering scenario causes multiple minor gas-rich mergers, and leads to the formation of a kinematically hot disk, thick disk population, at a high redshift. Once the mergers become less significant at a later epoch, the thin disk population starts building up. Because in this scenario the thick disk population forms intensively at high redshift through multiple gas-rich mergers, the thick disk population is compact and has systematically higher [α/Fe] abundance than the thin disk population. We discuss that the thick disk population would be affected by the formation of the thin disk and suffer from the radial migration, which helps the thick disk population to be observed in the solar neighborhood. In addition, we show that the current cosmological simulations also naturally predict that the thin disk population is flaring at the outer region. As shown in Rahimi et al. (2014), at high vertical height from the disk plane, the compact thick disk population (low metallicity and high [α/Fe]) is dominant in the inner region and the flaring thin disk population (high metallicity and low [α/Fe]) contributes more in the outer region. This helps to explain the positive radial metallicity gradient and negative radial [α/Fe] gradient observed at high vertical height in the Milky Way stellar disk.

1. Introduction

Geometrically thick disk in addition to the thin disk is found in external galaxies ubiquitously and in the Milky Way (Gilmore & Reid 1983). Despite many observational and theoretical studies of the thick disk, the origin of these thin and thick disks are still in debate. Brook et al. (2004) suggested high-z in-situ thick disk formation with gas-rich mergers, where we connected the thick and thin disk formation with a Λ-cold dark matter (ΛCDM)-based hierarchical clustering galaxy formation using N-body/smoothed particle hydrodynamics (SPH) simulations. We serendipitously found from numerical simulations that the thick disk formed at a high redshift, when there were multiple mergers of building blocks taking place. Because these building blocks are tiny galaxies and therefore gas rich, the stars mainly formed in-situ in the central disk after they merged. Because of the mergers, the central gas disk is kinematically hot. As a result, the stars formed from such gas disk is thick disk. Once the mergers stop at later epoch, the thin disk can start building up from the gas smoothly accreting. Hence, the thick disk formed before the thin disk formed. As discussed in Brook et al. (2004), this scenario resembles Jones & Wyse (1983) who suggested that a thick disk formed during a violent relaxation of the galactic potential, prior to the formation of the thin disk. However, the chaotic mergers of the gas-rich building blocks is also involved in the thick disk formation of Brook et al. (2004).

By analyzing the properties of the star particles at a radius similar to the solar radius in the Milky Way, we have demonstrated that this scenario naturally explains the age-velocity dispersion relation (Brook et al. 2004) and the two distinct populations in the chemical composition, e.g. [α/Fe] vs. [Fe/H] distribution, for the observed solar neighborhood stars (Brook et al. 2005). The picture is also consistent with the kinematically hot disk observed in the star forming galaxies at high redshift, where the disk has significantly lower rotation velocity vs. velocity dispersion ratio, $V/\sigma \sim 2-6$ (e.g. Genzel et al. 2008), compared with the low redshift disk galaxies, $V/\sigma \sim 10-20$. In Brook et al. (2006), we demonstrated that the disk is smaller and thicker in the early epoch when the thick disk is forming. It is also qualitatively consistent with the morphological evolution and effective radius evolution observed in the Milky Way progenitors (e.g. van Dokkum et al. 2013).

In this paper we summarize the recent progress in numerical simulation studies of the thick and thin disk formation along the scenario of the high-z in-situ thick disk formation with gas-rich mergers.

2. Chemically decomposed thick and thin disk populations

In Brook et al. (2012), we studied the properties of the chemically decomposed thick and thin disk populations using cosmological simulation data of much higher resolution and more realistic disk galaxy model simulated with an N-body/SPH code, Gasoline (Wadsley et al. 2004). As shown in Figure 1 of Brook et al. (2012), the galaxy builds up with multiple mergers at a high redshift, and the merging galaxies are gas-rich building blocks falling into the central galaxy. The disk at high redshift is thick and compact, because the mergers keep perturbing the central disk, which also leads to the angular momentum loss of the gas disk. After around $z \sim 1$, there are much less mergers as expected in a ΛCDM cosmology, and the galaxy builds up a larger and thinner disk from the smooth gas accretion.

First, the star particles are selected in the 'solar annulus' region which is defined as a region of $7 < R_{xy} < 8$ kpc and $|z| < 0.5$ kpc, where the disk is in the $x-y$ plane. These star particles show clearly different sequences in [O/Fe] vs. [Fe/H] plane. We therefore categorized the star particles to the thick disk population (stars around a sequence of higher [O/Fe]) and the thin disk population (stars around a sequence of lower [O/Fe]), and analyzed the properties of these two populations. We here follow the terminology of "population" used in Haywood et al. (2013) to describe the chemically defined different populations of the disk components. We found that the thick disk population is predominantly older than the thin disk population. In addition, the star particles selected in the solar annulus show the age-velocity dispersion relation with increasing velocity dispersion with age, which is consistent with the observed relation in the solar neighborhood stars. Therefore, the thick disk population is older and has higher velocity dispersion.

In that paper, we also showed that the old stars which were at the solar annulus at $z = 0$ formed in the inner region of the disk (mainly less than 5 kpc in this particular simulation), because the disk was smaller at that time. Then, the thick disk population stars migrated outwards to be seen at the solar radius. The radial migration is important for the thick disk population to be observed at solar neighborhood, because they formed at early epoch as a compact thick disk. In fact, the scale-length of the thick disk population was $h = 1.7$ kpc at $z = 1$ and became larger, $h = 2.3$ kpc, at $z = 0$. In the cosmological simulation, we do not think that we properly resolve the radial migration mechanism due to the spiral arm (Sellwood & Binney 2002; Grand et al. 2012), but this migration is mainly induced by the perturbation (Bird et al. 2012). However, in the real galaxy, as the thin disk builds up, the spiral arms also develop at larger and larger radii and induce the radial migration for both thin and thick disk population stars. The radial migration is more efficient for the kinematically colder stars. However, because there is a long time since the formation of thick disk population, even if the radial migration is inefficient for the kinematically hot thick disk population (Solway et al. 2012), they can be affected by the thin disk spiral arms, because the thin disk population grows bigger than the thick disk populations, and the thick disk stars migrate more outward.

Although the thick disk populations which formed as a compact and thick disk at a high redshift become larger due to the radial migration induced by the thin disk population, they cannot become larger than the thin disk. As a result, the scale length of the thick disk population becomes smaller than that of the thin disk population. In addition, because there is negative metallicity gradient in the thin disk population, the scale length of the metal poor thin disk population is larger than that of the metal rich thin disk population. This is consistent with the observed scale-length of the thin and thick disk populations (e.g. Bensby et al. 2011; Bovy et al. 2012).

Similar formation history of the thick and thin disk populations and their observational consequences are shown in Bird et al. (2013); Minchev et al. (2013); Stinson et al. (2013). This means that this scenario is a natural consequence of a disk galaxy formation in a ΛCDM cosmology.

3. Metal abundance distribution in Galactic disk

In Rahimi et al. (2014), we analyzed both the radial metallicity ([Fe/H]) and [α/Fe] gradients for a cosmologically simulated disk galaxy, which includes the detailed chemodynamical evolution with our original N-body/SPH simulation code, GCD+ (Kawata & Gibson 2003). Especially, we highlighted the radial gradients at large vertical height above the galactic disk, and compared them with those at the disk plane. We analyzed the metallicity and [α/Fe] radial gradients at the disk plane which was defined as stars within vertical height, $|z| < 1$ kpc, and the two regions of the different vertical height ranges of $1 < |z| < 2$ kpc and $2 < |z| < 3$ kpc. We found that the radial metallicity gradient in the disk plane was negative, i.e. the metallicity decreasing with radius, while the radial gradient was positive, increasing [Fe/H] with radius, at the high vertical height, $2 < |z| < 3$ kpc. This trend is consistent with the observed radial metallicity gradients at the different vertical heights in the Milky Way (e.g. Carrell et al. 2012). The negative radial metallicity gradient is naturally expected from higher star formation activities in

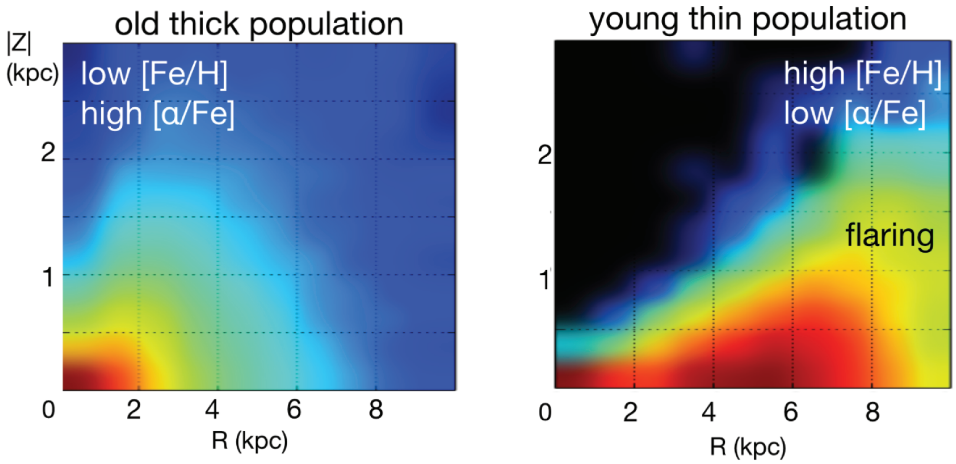

Figure 1. The distribution of older (left) and younger (right) disk stars in the |z| vs. R plane shown in Figure 4 of Rahimi et al. (2014). Bright (red) shows high density and dark (black) shows low density. From the right panel, we see that there is a hint of flaring at the outermost radii. We discuss that these younger and older disks are respectively analogs of old thick and young thin disk populations observed in the Milky Way.

the inner region. However, the positive radial metallicity gradient is not trivial to be explained. Therefore, Rahimi et al. (2014) further analyzed the numerical simulation data and investigated the origin of the positive radial metallicity gradient at the high vertical height which is obtained in the numerical simulation.

We have divided the sample of the disk stars into two groups: younger and older disk star particles.[1] Figure 1 shows the density distribution of the younger and older populations. Because the older population is compact and has high velocity dispersion (which is a natural outcome of the disk formation in a ΛCDM cosmology, as discussed in Section 2), they can reach $|z| > 2$ kpc at any radius in the inner region. On the other hand, the younger population has a lower velocity dispersion and develops a larger disk. Because the restoring force due to the gravitational potential of the disk is high at the inner radii, the younger stars are confined within lower vertical heights ($|z| < 1.5$ kpc) in the inner region. However, since the restoring force from the disk is weaker in the outer region, the younger population can reach higher vertical height. This induced a "flaring" feature in the right panel of Figure 1 for the younger stars. As a result, at the high vertical height, the older population is more dominant in the inner region, while in the outer region the younger population is more dominant, because of the flaring of the younger population and more compact older population. Since the older disk populations are more metal poor than the younger disk population, this can explain the positive radial metallicity gradient at the high vertical height.

[1]Rahimi et al. (2014) defined the younger (older) population as age< 3 (age> 3) Gyr, which is clearly inconsistent with the age range of the thick and thin disk populations in the Milky Way. However, we here discuss qualitative trend and find the reason why this particular simulated galaxy shows the positive metallicity gradient, which can be a possible mechanism to explain the observed positive metallicity gradient in the Milky Way.

Putting this qualitative trend into the context of the Milky Way disk, we can redefine the older population as the thick disk population, and the younger population as the thin disk population. Then, the positive radial metallicity gradient seen in the Milky Way at the high vertical height can be explained by more dominant metal poor thick disk population in the inner region and more dominant metal rich thin disk population in the outer region (Figure 1). In Rahimi et al. (2014), we predicted that if this is true, we should see a negative radial [α/Fe] gradient at the high vertical height, because the thick disk population has systematically higher [α/Fe] than the thin disk population. Recently, this prediction has been confirmed by several observational studies. For example, from Sloan Digital Sky Survey (SDSS), the Apache Point Observatory Galactic Evolution Experiment (APOGEE) data Anders et al. (2014) showed almost flat radial [α/M] gradient at $|z_{max}| < 0.4$ kpc, but a clear negative [α/M] gradient at $1.5 < |z_{max}| < 3$ kpc, where M stands for over all metal abundance and z_{max} is the maximum vertical amplitude from their orbital analysis. Rahimi et al. (2014) also predicted that there should be the negative radial age gradient for the disk stars at the high vertical height, which should be be able to be tested in the Milky Way as well as the external edge-on galaxies (see also Minchev et al. 2015).

These results in Rahimi et al. (2014) have been further supported by the recent studies using different cosmological simulations with different numerical simulation codes in Minchev et al. (2015) and Miranda et al. (2016). Unlike the two populations of the disks analyzed in Rahimi et al. (2014), Minchev et al. (2015) analyzed the structure of the disk stars within many different age bins, and demonstrated that there is a continuous trend that younger disk stars are larger and thinner, and flaring at more outer radius.

The compact and thicker thick disk population and larger, thinner and flaring thin disk populations can also qualitatively explain the [α/Fe] and [Fe/H] distributions observed in Nidever et al. (2014) and Hayden et al. (2015). From APOGEE data, they convincingly showed that at the high-vertical height ($1 < |z| < 2$ kpc) in the inner region ($R < 7$ kpc) the high-[α/Fe] thick disk population is dominant, and there are very few low-[α/Fe] thin disk population stars. On the other hand, in the outer region ($R > 9 - 11$ kpc), there is almost no thick disk population, while there is the dominant thin disk population. This trend can be naturally explained by the compact thick disk population and flaring thin disk population (see also Bensby et al. 2011).

Nidever et al. (2014) and Hayden et al. (2015) also showed that the thick disk populations follow always the same sequence in the [α/Fe] vs. [Fe/H] plane irrespective of the position in the disk. In other words, there is no radial metallicity gradient in the thick disk population (e.g. Bensby et al. 2011; Mikolaitis et al. 2014), and therefore the thick disk populations are chemically well-mixed (at least radially, but may not be so vertically, since the current observations, e.g. Mikolaitis et al. 2014, suggested a shallow negative vertical metallicity gradient). The well-mixed metal abundances are naturally predicated in the high-z gas-rich merger driven in-situ thick disk population formation as shown in Brook et al. (2005) and Bekki & Tsujimoto (2011). Alternatively, if the thick disk population is developed by the kinematical scattering from giant clumpy star forming regions in the gas-rich central disk at high redshift as suggested in Noguchi (1998), the chemical composition of the thick disk could be well mixed (e.g. Inoue & Saitoh 2014).

4. Geometrically defined thick and thin disks

Jurić et al. (2008) suggested that the thick disk scale length, $h = 3.9$ kpc, of the Milky Way is larger than the scale length of the thin disk, $h = 2.6$ kpc. This may sound contradictory to the above discussion of the compact thick disk population and the larger thin disk population. However, we note that this study defined thick and thin disks purely by spatial distribution of stars, but not by chemical properties. We here define this thick disk as "geometrically" thick and thin disks. Minchev et al. (2015) discussed that even if the chemically decomposed thick disk population is more compact than the thin disk population, the flaring thin disk population can contribute to the geometrically thick disk at the outer radii, and lead to a larger geometrically thick disk than the thick disk population. In addition, the overall stellar distribution does not have to show a clear flaring, because the scale-height of the geometrically thick disk structure is determined by the mixture of the thin and thick disk populations. The flaring thin population would be clearly identified, only when the populations are decomposed by the chemical abundances or the age.

5. Summary

As suggested in Brook et al. (2004), cosmological numerical simulations of the disk galaxy formation commonly predict the compact, thicker and old thick disk population and larger, thinner and younger thin disk population, because of the more gas-rich minor mergers at earlier epoch in a ΛCDM cosmology. In addition, as shown in Rahimi et al. (2014), the thin disk population is likely to be flaring in the outer region, which helps to explain the observed radial metal abundance distribution at the high vertical height in the disk. At least, the current observational data are not inconsistent with the predicted properties from such thick and thin disk (population) formation scenario. Still, there is a variety of the formation histories of the Galactic disk even within this scenario, and many remaining questions; e.g. how and when the transition from thick disk population formation phase to the thin disk population formation phase happened?, what was the original size of the thick disk population?, how the thin disk population has grown? inside-out (increasing scale-length) or keeping the constant scale-length? were the metallicity gradients constant, steeper or shallower at the earlier epoch? what is the mass ratio between thin and thick disk populations? how the thick and thin disk populations established the clearly distinguished sequences in [α/Fe]-[Fe/H] relation? The geometrical structures of the stars with different [α/Fe] (or age) ranges should be sensitive to the formation history of the Galactic disk. The combination of the upcoming Gaia data and the ground-based Galactic star surveys with multi-object spectrographs must help to unravel the geometrical structures of the chemically (or age) decomposed disk stars.

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