SDSS Observations of the Milky Way vs. N-body Models: A Comparison of Stellar Distributions in the Position-Velocity-Metallicity Space

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Abstract. The data obtained by the recent modern sky surveys enable detailed studies of the stellar distribution in the multi-dimensional space spanned by spatial coordinates, velocity and metallicity, from the solar neighborhood all the way out to the outer Milky Way halo. While these results represent exciting observational breakthroughs, their interpretation is not simple. For example, traditional decomposition of the thin and thick disks predicts a strong correlation in metallicity and kinematics at ∼1 kpc from the Galactic plane; however, recent SDSS–based work has demonstrated an absence of this correlation for disk stars. Instead, the variation of the metallicity and rotational velocity distributions can be modeled using non–Gaussian functions that retain their shapes and only shift as the distance from the mid–plane increases. To fully contextualize these recent observational results, a detailed comparison with sophisticated numerical models is necessary. Modern simulations have sufficient resolution and physical detail to study the formation of stellar disks and spheroids over a large baseline of masses and cosmic ages. We discuss preliminary comparisons of various observed maps and N–body model predictions and find them encouraging. In particular, the N–body disk models of Roškar et al. [1] reproduce a change of disk scale height reminiscent of thin/thick disk decomposition, as well as metallicity and rotational velocity gradients, while not inducing a correlation of the latter two quantities, in qualitative agreement with SDSS observations.

INTRODUCTION

Most studies of the Milky Way structure can be described as investigations of the stellar distribution in the nine–dimensional space spanned by the three spatial coordinates, three velocity components, and three main stellar parameters (luminosity, effective temperature, and metallicity). Recently, several SDSS–based studies have provided unprecedented observational constraints in various projections of this nine–dimensional space. Jurić et al. ([2], hereafter J08) used photometric parallax method to estimate distances to ∼48 million stars, and studied their spatial distribution. Thanks to accurate SDSS photometry that enabled reasonably accurate distances (10–15%, [3]), faint magnitude limits ($r < 22$), and a large sky coverage (6500 deg^2), J08 were able to robustly constrain the parameters of a model for global spatial distribution of stars in the Milky Way.

While their model is qualitatively similar to previous work exemplified by the Bahcall & Soneira [4] model, J08 detected abundant substructure, and a clear change of slope in the counts of disk stars as a function of distance from the Galactic plane, usually interpreted as the transition from the thin to thick disk [5]. Ivezić et al. ([6], hereafter I08) further extended global analysis of SDSS data by developing a photometric metallicity estimator, and by utilizing a large proper motion catalog based on SDSS and Palomar Observatory Sky Survey data [7]. I08 studied the dependence of metallicity and rotational velocity for disk stars on the distance from the Galactic plane and detected gradients of both quantities over the distance range from several hundred pc to several kpc. Such gradients would be expected in the traditional thin/thick disk decomposition where the thick disk stars have a well defined bulk rotational velocity lag and lower metallicity compared to those of the thin disk. However, such a model would also also predict a correlation between metallicity and the velocity lag, which is strongly excluded ($\sim 7\sigma$ level) by the I08 analysis. More sophisticated models are therefore needed. These, at minimum, have to answer the following questions:

1. Do the models reproduce the change of slope in the counts of disk stars as a function of distance from the Galactic plane?
2. If so, do they reproduce the gradients in metallicity and rotational velocity?
3. If so, are metallicity and rotational velocity uncorrelated?

If the answer to all these questions is yes, then the model may be used to extract further insight about the importance of various physical mechanisms operating in the disk of the Milky Way, and in particular it might allow us to study correlations of observables with stellar age and other quantities that are hard or impossible to measure directly.

SIMULATION

Here we analyze the results of an N–body + Smooth Particle Hydrodynamics (SPH) simulation designed to mimic the quiescent formation and evolution of a Milky Way–type galactic disk following the last major merger. The system is initialized as in Kaufmann et al. [8] and Roškar et al. ([1],[9], hereafter R08 and R08a respectively), and consists of a rotating, pressure–supported gas halo embedded in an NFW [10] dark matter halo. As the simulation proceeds, the gas cools and collapses to the center of the halo, forming a thin disk from the inside–out. When the gas reaches densities and temperatures conducive to star formation, the sub–grid star formation and stellar feedback recipes are initiated [11]. Importantly, the stellar feedback prescriptions include SN II, SN Ia and AGB metal production, as well as injection of supernova energy which impacts the hydrodynamic properties of the disk ISM. Note that we make no *a priori* assumptions about the disk's structure – its growth and the subsequent evolution of its stellar populations are completely spontaneous and governed only by hydrodynamics, stellar feedback, and gravity. Although we do not account for the full cosmological context, merging in the ΛCDM paradigm is a higher order effect at the epochs in question [12]. By simplifying our assumptions, we are able to use higher resolution and more easily study the impact of key dynamical effects to observational properties of stellar populations.

Based on these simulations, R08 and R08a presented the implications of stellar radial migration resulting from the interactions of stars with transient spiral arms [13] on the observable properties of disk stellar populations. Here we explore whether the picture of disk evolution presented in R08 and R08a may also help understand the correlations (and lack thereof) in the disk properties derived from SDSS data.

ANALYSIS AND DISCUSSION

To be consistent with the analysis of high galactic latitude SDSS data by J08 and I08, we select model particles from an annulus with 7 kpc $< R <$ 9 kpc, where R is the galactocentric cylindrical radius. We study the stellar mass distribution, rotational velocity and metallicity as functions of distance from the Galactic plane, Z. The behavior of model results in illustrated in Figure 1.

We find that the model distribution of stars as a function of Z resembles a sum of two exponential profiles, with the "break" height of $Z \sim 1.1$ kpc. The best-fit scale heights are 365 pc and 500 pc, in qualitative agreement with SDSS data [2]. Quantitatively, the scale height ratio suggested by data is higher ($\sim$3, instead of $\sim$1.4) and the "thick disk" normalization is $\sim$0.13, rather than $\sim$ 0.3. Nevertheless, since these models are not specifically tuned to reproduce the Milky Way, we find this agreement remarkable.

The age distribution as a function of Z shows that only very old stars are found at large Z: the median age is $\sim$7 Gyr at $Z \sim 1$ kpc. The rotational velocity depends on age: the older a star is, the slower is its rotation. Together with the change of age distribution with Z, this correlation leads to a Z gradient of rotational velocity: the best-fit value is 15 km/s, in qualitative agreement with the measured value of $\sim$30 km/s [6].

The metallicity distribution also changes with Z: the best-fit gradient is $\sim$0.12 dex/kpc, again in qualitative agreement with the measured value of $\sim$0.3 dex/kpc [6]. Although both rotational velocity and metallicity show vertical gradients, when stars are selected from a thin Z slice, velocity and metallicity are not correlated. Hence, the models of R08 are in qualitative agreement with the data and provide affirmative answers to all three questions posed in Introduction, at least in a qualitative sense.

In summary, the models of R08 show remarkable similarity to SDSS observations of the distribution of Milky Way stars in the position–velocity–metallicity space. In addition, these models provide a quantity that SDSS observations cannot – the stellar age. We intend to further explore the distribution of stellar age and its correlations to various observables in future work.

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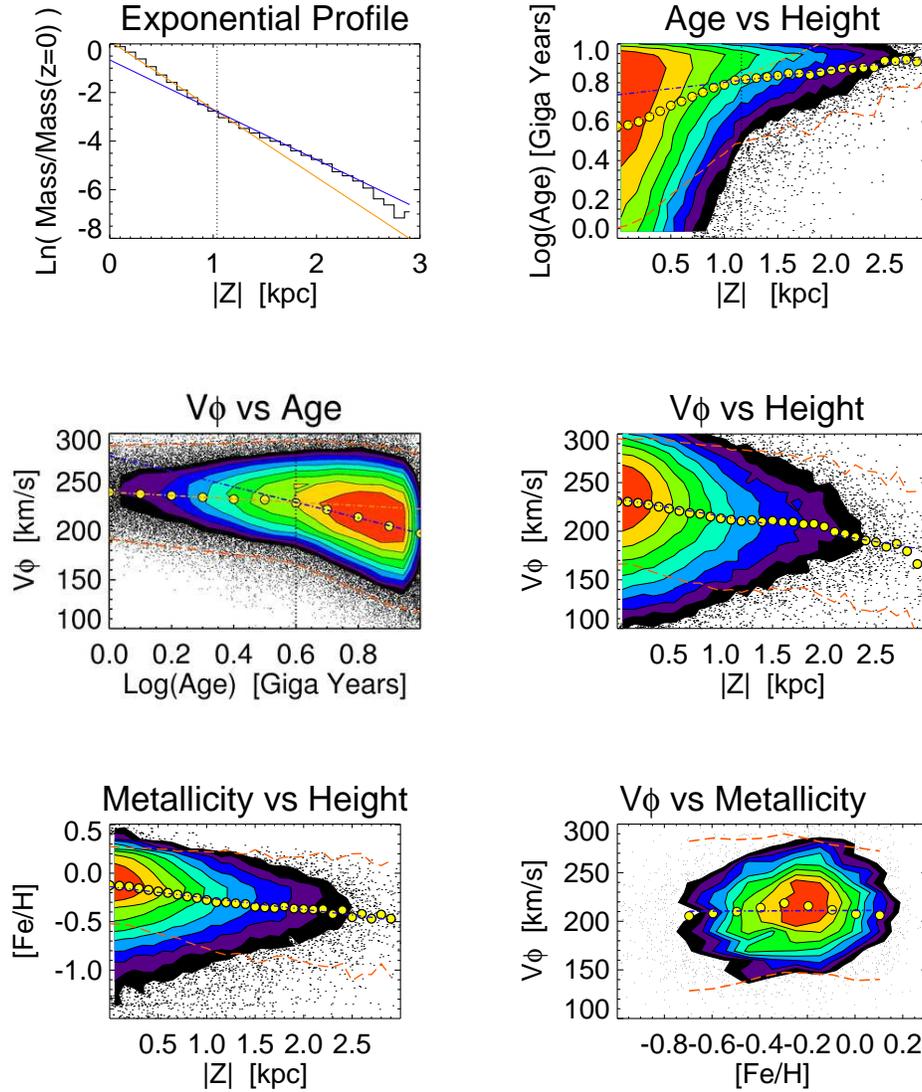13. J. A. Sellwood, & J. J. Binney, *MNRAS*, **336**, 785, (2002)

FIGURE 1. The behavior of ∼200,000 model particles selected from a galactocentric cylindrical annulus with 7 kpc < R < 9 kpc. The histogram in the top left panel shows mass-weighted counts as a function of distance from the Galactic plane, Z. The two solid straight lines show the best-fit thin and thick exponential density profiles, and the vertical dashed line marks the transition. The age distribution as a function of Z is shown in the top right panel as color-coded contours (low to medium to high: black to green to red) in the regions of high density of points, and as individual points otherwise. The large symbols show the median values in Z bins, and the dashed lines show a 2σ envelope around the medians. The dot-dashed line shows the best linear fit to these medians. The remaining four panels are analogous, except that they show the rotational velocity vs. age (middle left), the rotational velocity vs. Z (middle right), the metallicity vs. Z (bottom left) and the rotational velocity vs. metallicity (bottom right) diagrams. In the last panel, only a subset of data from a thin slice in Z centered at ∼1 kpc is shown. Note the absence of a correlation between the velocity and metallicity.