

Formation of the Galactic stellar halo: Origin of the metallicity-eccentricity relation

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ABSTRACT

Motivated by the recently improved knowledge on the kinematic and chemical properties of the Galactic metal-poor stars, we present the numerical simulation for the formation of the Galactic stellar halo to interpret the observational results. As a model for the Galaxy contraction, we adopt the currently standard theory of galaxy formation based on the hierarchical assembly of the cold dark matter fluctuations. We find, for the simulated stars with $[\text{Fe}/\text{H}] \leq -1.0$, that there is no strong correlation between metal abundances and orbital eccentricities, in good agreement with the observations. Moreover, the observed fraction of the low eccentricity stars is reproduced correctly for $[\text{Fe}/\text{H}] \leq -1.6$ and approximately for the intermediate abundance range of $-1.6 < [\text{Fe}/\text{H}] \leq -1.0$. We show that this successful reproduction of the kinematics of the Galactic halo is a natural consequence of the hierarchical evolution of the subgalactic clumps seeded from the cold dark matter density fluctuations.

Subject headings: Galaxy: abundance – Galaxy: evolution – Galaxy: halo

1. Introduction

Structure and dynamics of the metal-deficient halo component in the Galaxy provide valuable information on the early evolution of the Galaxy (e.g., Freeman 1987; Majewski 1993). Accordingly, the origin of the Galactic stellar halo has been extensively discussed by many authors since Eggen, Lynden-Bell, & Sandage (1962, hereafter referred to as ELS) reported a strong correlation between metal abundances and space motions of the high-velocity stars in the solar neighborhood. ELS argued that the contraction of the Galaxy must have been monolithic and rapid within a free-fall time ($\sim 10^8$ yr). Several authors however pointed out that the collapse time scale estimated by ELS is greatly affected by their selection criterion against the halo stars having high angular momentum (e.g., Yoshii & Saio 1979; Norris, Bessell, & Pickles 1985; Chiba & Yoshii 1998, hereafter CY). Alternatively, Searle & Zinn (1978, hereafter SZ) proposed that the Galactic halo was formed slowly ($\sim 10^9$ yr) by chaotic merging/accretion of several subgalactic fragments. It is yet unsettled whether either ELS's monolithic or SZ's merging picture (or both, e.g., Norris 1994; Freeman 1996; Carney et al. 1996) is more plausible and realistic for describing the early evolution the Galaxy.

Kinematic aspects of the Galactic metal-poor stars have been greatly improved by the recently completed *Hipparcos* Catalogue (ESA 1997) and various ground-based catalogs (e.g., Platais et al. 1998; Urban et al. 1998) which provide unprecedentedly accurate proper motion data for a wealth of metal-poor stars (Beers et al. 2000). Using the non-kinematically selected sample of stars having available proper motions, CY and Chiba & Beers (2000, hereafter CB) revisited the relation between metal abundances and orbital eccentricities of the halo stars and found no evidence for a strong correlation between these quantities, in contrast to ELS's finding. CB also showed a clear evidence for internal structure of the halo: the outer halo shows no systematic rotation and nearly

spherical density distribution, whereas the inner halo has a prograde rotation and a highly flattened density distribution. Also, Helmi et al. (1999) discovered a statistically significant clumpiness of the nearby halo stars in the angular momentum space, and argued that about 10 % of the halo come from a single small galaxy that was disrupted during or soon after the Galaxy formation. These new findings not only provide constraints on the formation of the Galactic stellar halo but also improve our understanding of how disk galaxies like our own form.

In this Letter, we address the question whether the above kinematic and chemical properties of the Galactic halo are understandable in the context of the currently favored theory of galaxy formation based on the hierarchical assembly of cold dark matter (CDM) halos (White & Rees 1978). Most of the CDM-based numerical models on disk galaxy formation have focused on only the fundamental properties of a disk, such as an exponential density profile (Katz 1992) and Tully-Fisher relation (Steinmetz & Navarro 1999). The spatial structure of the stellar halo has been examined by Steinmetz & Müller (1995), but the detailed internal kinematics of the halo stars in the simulated model remained unknown. Here we explore a numerical simulation for the formation of the Galactic halo, to investigate whether the CDM model can successfully explain the kinematic and chemical properties of the Galactic halo. We particularly focus on the evolution of hierarchically clustered subgalactic clumps seeded from the CDM density fluctuations and investigate their evolutionary effects on the orbital distribution of the stars in conjunction with the metal enrichment. More extensive analyses and results of the numerical simulations will be presented elsewhere (Bekki & Chiba 2000).

2. Model

The numerical method and technique for solving galactic chemodynamical evolution and models for describing star formation and dissipative gas dynamics are presented in Bekki & Shioya (1998), and here we briefly describe the initial conditions of protogalactic clouds, star formation law, and chemical evolution model. The way to set up initial conditions for numerical simulations of forming disk galaxy within a hierarchical clustering scenario is essentially the same as that adopted by Katz & Gunn (1991) and Steinmetz & Müller (1995). We here use the COSMICS (Cosmological Initial Conditions and Microwave Anisotropy Codes), which is a package of fortran programs for generating Gaussian random initial conditions for nonlinear structure formation simulations (Bertschinger 1995; Ma & Bertschinger 1995). We consider an isolated homogeneous, rigidly rotating sphere, on which small-scale fluctuations according to a CDM power spectrum are superimposed. The mass ratio of dark matter to baryons is 9.0 and both components have the same initial distribution. The initial total mass, radius, and spin parameter (λ) of the sphere in the present model are $6.0 \times 10^{11} M_{\odot}$, 45 kpc, and 0.08, respectively. For cosmological parameters of $\Omega = 1.0$, $q_0 = 0.5$, and $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$ adopted in the present study, the initial overdensity δ_i of the sphere in the fiducial model is estimated to be 0.29 corresponding to a 2.5σ overdensity of a biased CDM spectrum on a mass-scale of $6.0 \times 10^{11} M_{\odot}$ with a biasing parameter $b = 2$. We start the simulation at the redshift $z = 25$ and follow it till $z = 0$ corresponding to the age of the universe equal to 13 Gyr. Initial conditions similar to those adopted in the present study are demonstrated to be plausible and realistic for the formation of the Galaxy (e.g., Steinmetz & Müller 1995).

Star formation is modeled by converting the collisional gas particles into collisionless new stellar particles according to the Schmidt law (Schmidt 1959) with the exponent of 2 and the coefficients in the law are taken from the work of Bekki (1998). The collisional and

dissipative nature of the interstellar medium are modeled according to the sticky particle method (Schwarz 1981) with the cloud radius (r_{cl}) of 450 pc and we consider multiple collisions among clouds (see Bekki & Shioya 1998 for details). The total particle number used for modeling the initial sphere is 14147 both for dark matter and for baryons (gas and new stars), which means that the mass of each particle is $3.8 \times 10^7 M_{\odot}$ for dark matter and $4.2 \times 10^6 M_{\odot}$ for baryons. We assume the local mixing of metals, in such a way that those produced by a new star are instantaneously assigned to the gas particles located within $2r_{cl}$ from the star. The fraction of gas returned to interstellar medium in each stellar particle and the chemical yield are 0.3 and 0.02, respectively. All the calculations related to the above chemodynamical evolution have been carried out on the GRAPE board (Sugimoto et al. 1990) at Astronomical Institute of Tohoku University. The parameter of gravitational softening is set to be fixed at 0.053 in our units (2.4 kpc). The time integration of the equation of motion is performed by using the 2nd-order leap-frog method.

Using the above model, we derive the distribution of metal abundances ($[Fe/H]$) and orbital eccentricities (e) of the stars with $[Fe/H] \leq -0.6$ at the epoch $z = 0$. Here e for each stellar particle is defined as:

$$e = \frac{r_{apo} - r_{peri}}{r_{apo} + r_{peri}} \quad (1)$$

where r_{apo} and r_{peri} are apo-galactic and peri-galactic distances from the center of the simulated Galaxy, respectively. For estimating e , we first select the stellar particles with $[Fe/H] \leq -0.6$ found at $z = 0$. Then we calculate the time evolution of their orbits under the gravitational potential of the simulated disk Galaxy achieved at $z = 0$ for ten dynamical time scale (~ 1.8 Gyr), and then estimate e . In order to avoid the contamination of metal-poor bulge stars in this estimation, we select only particles with their apo-galactic distances ranging from 8.5 to 17.5 kpc. In the followings, we use the symbol $[Fe/H]$ as the total metal abundance instead of the symbol Z to avoid confusion with redshift, although the current model does not consider the evolution of each element separately.

EDITOR: PLACE FIGURE 1 HERE.

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3. Result

Figure 1 shows the dynamical evolution of the star-forming gas sphere of the Galaxy in the present CDM model. The largest density maxima within the initial gas sphere become first non-linear ($z \sim 10$) and then collapse to form subgalactic clumps consisting of gas and new stars. Firstly born stars with old ages (> 10 Gyr) and low metallicities ($[\text{Fe}/\text{H}] < -3$) are located within these clumps till they are disrupted by later mutual merging. The initial gas sphere reaches the turn-around point at $z \sim 3.25$ and then begins to collapse. Subgalactic clumps developed from local small-scale density perturbations within the gas sphere fall onto the inner region of the proto-Galaxy owing to dynamical friction ($1.8 < z < 2.6$) and then merge with each other ($1.3 < z < 1.8$), leaving a compact disk ($z = 1.3$). Star formation rate is maximum ($\sim 30 M_{\odot} \text{ yr}^{-1}$) at the epoch of the dissipative merging between two massive clumps ($z \sim 1.5$). Gradual accretion of diffusely distributed gas onto the compact disk results in the growth of a thin disk between $z = 1.3$ and $z = 0.4$. These results are basically in agreement with earlier numerical results by Katz (1992) and Steinmetz & Müller (1995).

Figure 2 shows how the metal-poor halo with $[\text{Fe}/\text{H}] \leq -1.6$ is formed during the collapse of the Galaxy. Clearly, a significant fraction of the metal-poor stars ($\sim 50\%$) have already been formed within local small-scale density maxima at early epoch $z > 2.6$. These numerous clumps then merge with one another and the debris stars constitute the outer part of the halo. Later, the two massive subgalactic clumps are developed from the assembly

of smaller clumps and subsequently merge with each other. The stars confined within the clumps are consequently disrupted and spread over the inner region of the proto-Galaxy ($1.3 < z < 1.8$). As a consequence of this last merging event, the flattened structure of the inner halo is formed. The radial density distribution of the halo at $R \leq 20$ kpc follows roughly $\rho(R) \propto R^{-3.5}$, where R is the distance from the center of the disk (Bekki & Chiba 1999). These structural properties of the simulated halo are in good agreement with the corresponding observational results as reported by CB.

Figure 3 shows that there is no significant correlation between $[\text{Fe}/\text{H}]$ and e for the stars with $[\text{Fe}/\text{H}] \leq -0.6$, and that the existence of low eccentricity ($e < 0.4$), low metallicity ($[\text{Fe}/\text{H}] < -1$) stars is successfully reproduced in the present CDM model. This may be explained in a following manner.

First, as ELS argued, the rapid contraction of a gravitational potential within a dynamical time ($\sim 10^8$ yr) results in the transformation of initially nearly circular (smaller e) orbits to very eccentric (larger e) ones. On the other hand, the eccentricities of the orbits remain basically unchanged if the contraction is slow enough ($\sim 10^9$ yr). In the present CDM model, the time scale for the contraction of the Galaxy is lengthened by the expanding background universe (the time scale for which a proto-Galactic sphere with a turn-around radius of ~ 100 kpc is of the order of Gyr), so that the process of star formation mainly triggered by merging of small clumps is rather extended (~ 2 Gyr). Thus, the orbital eccentricities of the metal-poor stars, once formed, are not greatly influenced by the change of an overall gravitational potential of the Galaxy. Second, as we mentioned above, most of the metal-poor stars have been confined within the massive clumps, where their orbits are gradually circularized due to dissipative merging with smaller clumps and dynamical friction with the dark halo particles. Thus, a finite fraction of the debris stars after the last merging event preserve the orbital angular momentum of the clumps. Both

of these processes may give rise to the existence of low- e , low- $[\text{Fe}/\text{H}]$ stars in the simulated Galactic halo.

To be more quantitative, we plot, in Figure 4, the cumulative e distributions of the metal-poor stars with $[\text{Fe}/\text{H}] \leq -1.6$ (solid line) and $-1.6 < [\text{Fe}/\text{H}] \leq -1.0$ (dotted line). For the halo component with $[\text{Fe}/\text{H}] \leq -1.6$, the fraction of the simulated low- e stars with $e < 0.4$ is about 0.17, which is in good agreement with the observational result of about 0.2 (CY; CB). Also, as is consistent with the observational result, the cumulative e distribution in the intermediate abundance range $-1.6 < [\text{Fe}/\text{H}] \leq -1.0$ is systematically larger than that for $[\text{Fe}/\text{H}] \leq -1.6$. The fraction of the simulated low- e stars with $e < 0.4$ in this abundance range (~ 0.45) is somewhat larger than the observation (~ 0.35), suggesting that the metal-weak thick disk component, which is emerged in this intermediate abundance range, is somewhat over-produced. Besides this small deviation from the observation, we conclude that the reported kinematic and chemical properties of the Galactic halo are basically understandable in the context of the CDM-based model for the Galaxy contraction.

EDITOR: PLACE FIGURE 3 HERE.

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4. Discussion and conclusion

Although both the ELS monolithic and SZ merger scenarios have offered the basic ingredients for describing the early evolution of the Galaxy, either model alone does not comprehensively explain the currently improved knowledge on the fundamental properties of the halo (e.g., Freeman 1996; CB). For example, the lack of the abundance gradient in

the halo stars (Carney et al. 1990; CY) and no significant correlation between $[\text{Fe}/\text{H}]$ and e (CY; CB) are difficult to interpret in the context of the ELS scenario. The SZ scenario seems unlikely to explain a large vertical gradient of the mean rotational velocity $\langle V_\phi \rangle$ in the halo component (CB). It is also unclear how the rapidly rotating disk component subsequently formed after the totally chaotic merging of “Searle & Zinn” fragments. In contrast, to explain the dual nature of the observed halo in its density, kinematics, and age (Norris 1994; Carney et al. 1996; CB), one requires the sort of hybrid picture, combining aspects of both the ELS and SZ scenarios.

As a possible candidate model to achieve the above hybrid picture, we have considered the CDM model, which invokes both the hierarchical assembly of subgalactic clumps and the dissipative process of gas inside the clumpy protogalactic system. As a first step toward understanding the formation of the Galactic halo in this context, we have investigated the orbital properties of the stars in the simulated Galactic halo, and have shown that the hierarchical merging of CDM clumps in the course of the expansion and contraction of the overall protogalactic sphere plays a vital role in determining the observed $[\text{Fe}/\text{H}]-e$ relation of the metal-poor stars. It is also found that the dissipative merging of the clumps is important for the development of the characteristic structure of the halo and also for the subsequently formed disk component (Bekki & Chiba 2000).

While we have reproduced the most basic relation between metal abundances and orbital eccentricities of the halo stars based on the currently favored picture of galaxy formation, there are still a couple of points to be clarified for the comprehensive understanding of the halo formation. For example, Sommer-Larsen et al. (1997) reported that the velocity ellipsoid of the metal-poor stars changes from radial anisotropy near the Sun to tangential anisotropy in the outer part of the Galactic halo. This may be explained via the anisotropic, *dissipative* merging between protogalactic gas clouds in a collapsing

galaxy (Theis 1997), but it is yet unsettled as to whether the similar process is equally applied in the case of the CDM clumps consisting of both dissipationless particles (dark matter and stars) and dissipative gas. Also, the non-kinematically selected sample of the nearby stars shows a remarkable discontinuity of the mean rotational velocity, V_{rot} , at $[Fe/H] \sim -1.7$: the stars at $[Fe/H] < -1.7$ shows an approximately constant rotation, whereas those at $[Fe/H] > -1.7$ show the linear increase of V_{rot} with increasing $[Fe/H]$ (e.g., CB). We will further discuss in the forthcoming paper whether these other kinematic properties of the Galactic halo are also explained by the dynamical evolution of the system of subgalactic clumps seeded from the CDM density fluctuations.

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Fig. 1.— Mass distribution of the forming Galaxy projected onto the $x - z$ plane at each of redshifts ($z = 25, 2.6, 1.8, 1.3, 0.45,$ and 0) in the present CDM model of galaxy formation. Cyan and magenta colors represent gas and stars, respectively, and dark matter particles are not plotted here for clarity. Each frame measures 126 kpc on a side.

Fig. 2.— Mass distribution projected onto the $x - z$ plane at each of redshifts ($z = 2.6, 1.8, 1.3,$ and 0) for gaseous and stellar particles that finally become metal-poor stellar halo component with metallicity $[\text{Fe}/\text{H}] \leq -1.6$ at $z = 0$. Each frame measures 126 kpc on a side. Here, if a progenitor of a metal-poor halo star (i.e., a progenitor of a stellar particle with $[\text{Fe}/\text{H}] \leq -1.6$ at $z = 0$) is still gaseous at a given redshift, it is represented by cyan, whereas if the progenitor already exists as a star at a given redshift, it is represented by magenta. For example, about 50 (6) % of the metal-poor halo stars are still gaseous at $z = 2.6$ (1.3). Note that all particles at $z = 0$ are stars represented by magenta. At $z = 0$, the mass fraction of these metal-poor stars distributed in the halo, compared with the total baryonic mass of the system, is 0.014. The mean age of the stellar halo with $[\text{Fe}/\text{H}] \leq -1.6$ is about 10.5 Gyr.

Fig. 3.— Relation between metal abundances ($[\text{Fe}/\text{H}]$) and orbital eccentricities (e) for the simulated metal-poor stars with $[\text{Fe}/\text{H}] \leq -0.6$. Note the existence of low- e , low- $[\text{Fe}/\text{H}]$ stars in the simulated halo.

Fig. 4.— Cumulative e distributions, $F(< e)$, in the two abundance ranges of $[\text{Fe}/\text{H}] \leq -1.6$ (solid line) and $-1.6 < [\text{Fe}/\text{H}] \leq -1.0$ (dotted one).







