On the Origin of High-eccentricity Halo Stars

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Abstract. The present-day chemical and dynamical properties of the Milky Way are signatures of the Galaxy’s formation and evolution. Using a self consistent chemodynamical evolution code we examine these properties within the currently favoured paradigm for galaxy formation - hierarchical clustering within a CDM cosmology. Our Tree N-body/Smoothed Particle Hydrodynamics code includes a self-consistent treatment of gravity, hydrodynamics, radiative cooling, star formation, supernova feedback and chemical enrichment. Two models are described which explore the role of small-scale density perturbations in driving the evolution of structure within the Milky Way. The relationship between metallicity and kinematics of halo stars are quantified and the implications for galaxy formation discussed. While high-eccentricity halo stars have previously been considered a signature of “rapid collapse”, we suggest that many such stars may have come from recently accreted satellites.

Keywords: Milky Way, galaxy formation, Galactic halo

1. Introduction
The “monolithic collapse” versus “satellite accretion” debate surrounding galaxy formation is a classic one, and one which received attention once again at this Euroconference III. The former scenario was best expressed by Eggen, Lynden-Bell & Sandage (1962, hereafter ELS); supporting evidence for the ELS picture came from the apparent positive correlation between eccentricity and metallicity of halo stars. However, current cosmological theories of structure formation have more in common with accretion-style scenarios like that envisioned by Searle & Zinn (1978). Evidence in support of the latter can be found in the observations of stellar phase space substructure in the Galactic halo (e.g. Helmi et al. 1999).

We were motivated to run a grid of chemodynamical simulations with the intention of contrasting the effects of the two collapse scenarios on the evolution of the Milky Way. The two models described here vary primarily in their degree of clustering, and we examine the properties of the resulting simulated galaxies, in order to uncover present-day “signatures” of the model initial conditions and evolution. Here, we focus on the distribution of halo star orbital eccentricities.
Figure 1. $x - y$ plots of model 1 (upper panels) and model 2 (lower panels). The $z$ axis is the initial rotation axis. Grey dots represent gas particles, while black represent star particles. Epochs are chosen so that roughly the same stellar mass is present in corresponding upper & lower panels. Gas collapse and star formation are more centralised in model 2.

2. The Code and Models

Our Galactic ChemoDynamical code (GCD+) models self-consistently the effects of gravity, gas dynamics, radiative cooling, and star formation. Type Ia and Type II supernova feedback is included. We relax the instantaneous recycling approximation when monitoring the Galactic chemical evolution. Details of GCD+ can be found in Kawata & Gibson (2003, in prep); an earlier version of the code is described in Kawata (2001).

The semi-cosmological version of GCD+ used here is based upon the code of Katz & Gunn (1991). The initial condition is an isolated sphere of dark matter and gas, onto which small scale density fluctuations are superimposed (parameterised by $\sigma_8$). These perturbations are the seeds for local collapse and subsequent star formation. Solid-body rotation is imparted to the initial sphere; this determines whether a disk-like or elliptical galaxy results. For the models described here, relevant parameters include the total mass ($5 \times 10^{11} M_\odot$), baryon fraction ($\Omega_b = 0.1$), and spin parameter ($\lambda = 0.0675$); we employed 38911 dark matter and 38911 gas/star particles.

Again, the two models described here differ only in the value of $\sigma_8$. In model 1, $\sigma_8 = 0.5$, as favoured in standard CDM ($\Omega_0 = 1$) cosmology. In model 2, $\sigma_8 = 0.04$, a smaller value which results in a more rapid, dissipative, collapse.
3. Results

Figure 1 demonstrates the classical hierarchical merging in action in both models 1 (upper panels) and 2 (lower panels). Gas particles are marked in grey, while star particles are in black. Star formation occurs in overdense regions, seeded by the initial small-scale perturbation spectrum. Stars continue to form in sub-clumps, as well as in the central region of the disk galaxy as it is built up. We see less clustering in model 2 with most of the star formation occurring in the central region of the galaxy.

We analysed the bulk properties of the models at $z=0$ and confirmed that they were consistent with those of Berczik (1999) and Bekki & Chiba (2001). The predicted surface density profiles, metallicity gradients, and rotation curves for our two models did not differ significantly. However, we did find a difference in the distribution of the eccentricities of the orbits of solar neighbourhood halo stars.

The histogram of Figure 2a shows the eccentricity distribution of halo star particles ([Fe/H]$<-0.6$) in the solar neighbourhood for the two models. Each bin shows the fraction of such star particles falling in a given eccentricity range. Also shown are observations from Chiba & Beers (2000, hereafter CB). Model 1 produced a greater number of high eccentricity (ecc $>0.8$) solar neighbourhood halo stars, and is in better agreement with observation.

We next examined the specific accretion history of each model, tracing the eccentricity distribution functions for the stars associated with each disrupted satellite. We identified satellites at $z=0.46$ which have...
merged into the halo of the host galaxy by $z=0$. The histogram of Figure 2b shows the eccentricity distribution of solar neighbourhood halo stars which originated in these recently accreted satellites. The $y$-axis is normalised by the total number of solar neighbourhood halo stars in each eccentricity bin. Our primary conclusions are that the majority of these halo stars are of high-eccentricity, and that one satellite in particular contributes $\sim20\%$ of all high eccentricity halo stars in the solar neighbourhood at $z=0$. The reader is directed to the complementary study of Steinmetz et al. (these proceedings) which finds that stars from accreted satellites which were on polar orbits form part of the galaxies halo.

4. Conclusions
The key question we wish to address remains ... what are the implications for the competing galaxy formation paradigms? A brief response is as follows: CB observationally found no correlation between eccentricity and metallicity for halo stars near the Sun (their Figure 6a), obviating the need for a “rapid collapse” picture of the formation of the Galaxy (ELS). However, CB do identify a clump of high-eccentricity low-metallicity ([Fe/H] $\sim-1.7$) stars in this observational plane. In terms of ELS, they interpret this clump as a relic of a rapid collapse phase. Our simulations suggest that this clump is, more likely, evidence of recent satellite accretion in the Galactic halo.

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