Formation of the Galactic Halo

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Abstract. Recent observational and theoretical work suggests that the formation of the Galactic stellar halo involved both dissipative processes and the accretion of subfragments. With present data, the fraction of the halo for which an accretion origin can be substantiated is small, of order 10 percent. The kinematics of the best halo field star samples show evidence for both dissipative and dissipationless formation processes. Models of star-forming dissipative collapse, in a cosmological context and including feedback from star formation, do not confirm the simple relations between metallicity, rotation velocity, and orbital eccentricity for halo stars as originally predicted. The new model predictions are much closer to the observed distributions, which have generally been interpreted as evidence for an accretion origin. These results are broadly consistent with a hierarchical galaxy formation model, but the details remain to be worked out.

1. Introduction

In our quest to understand the formation of galaxies, the Milky Way takes a special place. Nowhere else can the properties of stellar populations be observed in comparable detail, can ages, metallicities, and kinematics be determined for as many individual stars. The Galactic stellar halo, the topic of this article, gives a vivid illustration: with its mass of only some $10^9 \, M_\odot$ and estimated surface brightness near the Sun of 27.7 V mag/arcsec$^2$ (Morrison 1993) it would be hard to observe at all in external galaxies. Yet it is believed to be the oldest component of the Galaxy, and to hold important information about the Milky Way’s formation process.

The early debate and even much of the recent discussion about the formation of the Galactic stellar halo focussed on two contrasting scenarios. One view, based on an apparent correlation between the metallicities and the orbital velocities and eccentricities of halo stars, held that the halo formed in a rapid dissipative collapse phase during which metal enrichment took place (Eggen, Lynden-Bell & Sandage 1962, ELS). The other, based on the lack of abundance gradient in the halo globular clusters and a $\sim 10^8$ yr age spread inferred from their horizontal branch colours, proposed that that the Galactic halo formed by the prolonged, chaotic accretion of dwarf galaxy-like fragments (Searle & Zinn 1978). Because in modern samples of low-metallicity halo stars no correlation is
in fact found between metallicity and kinematics (Norris 1986, Carney, Latham & Laird 1990, Chiba & Beers 2000), and because of direct evidence for accretion such as in the form of the Sgr dwarf galaxy (Ibata, Gilmore & Irwin 1994), the accretion scenario has become the standard view in the field (Freeman & Bland-Hawthorne 2002).

However, recent observational and theoretical developments suggest that some revision of this picture may be necessary. The fraction of the halo for which an accretion origin can be substantiated with present data is only of order 10 percent (Section 2). Modern analysis shows no evidence of an age spread for the metal-poor globular clusters within an error of $\sim 10^9$ yr; these are consistent with being old and coeval (Rosenberg et al. 1999, Salaris & Weiss 2002). Only intermediate metallicity clusters around $\sfrac{\text{[Fe/H]}}{2} \sim -1.2$ show evidence for an age spread of $2 - 3$ Gyr. From the new large samples of halos stars there is evidence for both dissipative and dissipationless processes during halo formation (Section 3). Recent models of dissipative collapse, in a cosmological context and including feedback from star formation, show that the predictions of the ELS model on which much of this discussion is based are oversimplified and partly incorrect (Section 4). And finally, in the current hierarchical models for structure formation in the Universe, accretion may occur both in a smooth, dissipative form and through the merging of subunits. In the hierarchical framework, the interesting question regarding the origin of the halo is not “dissipative collapse or merging?”, but

- how important was smooth accretion compared to lumpy accretion or merging?
- did small units form stars before they fell together?
- were infalling subunits tidally disrupted in the halo or did they survive into the disk or center?

Understanding the formation of the Galactic halo from the observed properties of its constituents will help in answering these questions within the more general problem of galaxy formation in hierarchical models of structure formation in the Universe.

2. Evidence for accretion

The most dramatic case for accretion in the Galactic halo is provided by the disrupting Sagittarius dwarf galaxy discovered by Ibata, Gilmore & Irwin (1994). The Sgr dwarf is visible over some $20^\circ \times 8^\circ$ on the sky, centered at (l,b)$\simeq (6^\circ, -14^\circ)$, at a galactocentric distance of 16 kpc on the other side of the Galactic center. It is orientated roughly perpendicular to the Galactic plane along its orbit. Sgr contains $L_V \simeq 1 - 2 \times 10^7 L_{\odot}$ of stars, 4 globular clusters, and probably $\sim 10^9 M_{\odot}$ of dark matter, which are in the process of being added to the Galactic halo (Ibata et al. 1997). The extended stream of previously dissolved stars has been found in several surveys.

With time, such streamers will phase-mix and become invisible in photometric surveys unless confined to particular orbital planes. However, substructure
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in phase-space is preserved much longer, once the Galactic potential has settled and evolves only slowly. Helmi et al. (1999) identified one sub-group of halo stars in a Hipparcos sample which they identified as the remains of an ancient accretion event. This subgroup was confirmed by Chiba & Beers (2000) in their larger sample of halo stars. According to these authors, the total mass of the precursor object is a few percent of the present Galactic halo, i.e., similar to that of the Sgr dwarf. New surveys based on halo Carbon stars (Ibata et al. 2001), RR Lyrae stars (Vivas et al. 2001), SDSS (Newberg et al. 2002), and GDSS (Kundu et al. 2002) have found at most a very small number of streams other than the Sgr stream. At least half the halo Carbon stars appear to belong to the Sgr stream according to Ibata et al. (2001), severely limiting the amount of stars that can have been accreted in the last 5 Gyr.

Thus from present data, the fraction of the Galactic halo for which there is evidence for accretion is of order 10%. This is in some contrast to the prediction of Bullock, Kravtsov & Weinberg (2001), who find that in hierarchical CDM models a large number of tidal streams from disrupted dwarf galaxies should make up a large fraction of the Galactic stellar halo. One way out would be that many of the small dark matter lumps predicted in CDM never made stars (see, e.g., Bullock, Kravtsov & Weinberg 2001, Stoehr et al. 2002). Alternatively, it is possible that the planned GAIA satellite will in fact detect halo substructure for a much larger fraction of halo stars, but on much finer scales. This would be the signature expected from accretion events during the early formation of the Galaxy, now in a more advanced state of phase-mixing, or from accretion of much smaller units. However, in this case the interpretation must involve questions about star formation issues as well. What are the smallest and what are the typical star-forming units in a Galactic collapse? In the Galactic disk, there is clearly structure on the scale of giant molecular clouds up to $\sim 10^6 M_\odot$. And how can we distinguish between an inevitably lumpy and prolonged collapse, and the accretion of separate fragments?

3. Evidence from halo star properties

There is general agreement that the Galactic halo is the oldest component of the Milky Way. The most metal-poor globular clusters with $[\text{Fe/H}] < -1.5$ are old and coeval, with age $12 \pm 1$ Gyr (Rosenberg et al. 1999, Salaris & Weiss 2002). Intermediate metallicity clusters around $[\text{Fe/H}] \sim -1.2$ show evidence for an age spread of $2 - 3$ Gyr and a slightly younger age. Halo field stars with $[\text{Fe/H}] < -1.8$ have red turnoff colours $B-V \approx 0.4$, and comparison with isochrones likewise indicates old ages. Only a small fraction of stars at higher metallicities have bluer turnoff colours, limiting the number of dwarf galaxies with intermediate age populations that could have been accreted (Unavane, Wyse & Gilmore 1996).

A detailed analysis of 1200 stars with $[\text{Fe/H}] \leq -0.6$, distance estimates, radial velocities, and proper motions was published by Chiba & Beers (2000). From this large, kinematically unbiased sample they deduced some noteworthy properties of Galactic halo stars: There is no correlation between $[\text{Fe/H}]$ and orbital eccentricity $e$ for the metal-poor stars, demonstrating that the evidence given by Eggen et al. (1962) is a result of kinematic bias. However, there is a
concentration of halo stars on radial orbits at \([\text{Fe/H}] \approx -1.7\), which may be a signature of early collapse, and a concentration of disk stars on near-circular orbits at \([\text{Fe/H}] > -1\). Other than this, the \([\text{Fe/H}]-\text{eccentricity}\) diagram is populated remarkably uniformly; even at the lowest abundances, \(\sim 20\%\) of the stars have \(e < 0.4\). Furthermore, while confirming the absence of a correlation of rotation velocity with \([\text{Fe/H}]\) for \([\text{Fe/H}] \leq -1.5\), Chiba & Beers (2000) find a decrease of rotation velocity with vertical height even for the lowest metallicity halo stars. This they interpret as a signature of dissipative formation of the inner halo. The inferred density distribution of the halo is nearly spherical in the outer region beyond \(R = 15 - 20\, \text{kpc}\), and highly flattened in the inner region. Studying the halo star orbits while slowly removing the Galactic disk potential, Chiba & Beers (2001) concluded that the inner halo prior to disk formation must have been substantially rounder than now, with axis ratio \(c/a \approx 0.8\), but still more flattened than the outer halo.

Based on their results, Chiba & Beers (2000) argue for a hybrid picture, in which the inner halo formed by dissipative contraction, while the outer halo was made mainly by the accretion of subgalactic fragments. (They discuss previous related ideas.) This would also be consistent with the tangentially anisotropic velocity distribution of BHB field stars at large distances inferred by Sommer-Larsen et al. (1997). However, because no division of the inner and outer halo components is visible in either the density profile or the rotation properties, this suggests that both dissipative and dissipationless processes may have occurred simultaneously at each radius, with the dissipationless processes relatively more important at larger radii. As discussed below, this would fit in quite naturally with the evolution expected in clumpy collapses in CDM models.

4. Modern dissipative collapse models

In modern computer models, it is possible to simulate the collapse, dissipation, star formation, and enrichment in an assembling galaxy in considerable detail, including the effects of a two-phase medium and of the feedback from supernovae. To compare with the abundances and kinematics of halo stars, one must follow the enrichment and kinematics of successive stellar generations. In such a simulation, it is not yet possible to follow the entire evolution from the initial gravitational clustering in the large-scale CDM universe to the late high-resolution baryonic processes. A number of simplifying assumptions must therefore be made, as is also the case in, e.g., the well-known semi-analytic models. In particular, in the absence of a quantitative theory of star formation, simple recipes for star formation rates must be used which, however, can be calibrated against observed star formation rates such as those of Kennicutt (1998).

In a recent model, Samland & Gerhard (2003) followed the dynamical collapse and star formation of a massive disk galaxy within a growing ΛCDM dark matter halo, whose mass evolves according to the cosmological simulations of the VIRGO-GIF project (Kauffmann et al. 1999). Small-scale structure and merging in the halo were ignored; this also by-passes the so-called angular momentum problem. The baryonic matter falls in with the dark matter. Both have the same angular momentum distribution, which corresponds to \(\lambda = 0.05\).
and is similar to the universal distribution found by Bullock et al. (2001). The model includes two interstellar medium phases, one a hot gas fluid, the other a cold/warm cloud medium. These phases and the stars interact through a number of processes, including the energy release and enrichment from young stars and supernovae. Stars form from the cold phase with a rate approximately $\propto \rho^{3/2}$, and are subsequently followed by an N-body code. Due to the macroscopic description of these processes, the model contains several parameters which are not well-determined theoretically. However, most of these can be calibrated against observations and, because of the self-regulating nature of the interactions, the dependence of the physical variables on these parameters is only modest.

The disk galaxy that forms in this model has about three times the mass of the Galaxy and is not a special model of the Milky Way. However, several results emerged which are of relevance for the formation of the Galactic halo. (1) The feedback from supernovae is important especially at early times when the potential of the dark matter halo is still shallow. Thus, the collapse and formation of the most metal-poor component ([Fe/H]< $-1.9$) takes about 1 Gyr, significantly longer than their dynamical time. (2) As a result, there is no dependence of rotation velocity on metallicity for these extreme halo stars; see Fig. 1. This relation only emerges at higher metallicities, at [Fe/H] $\simeq -1.8$, similar as for the observed halo stars. (3) Using the distribution in Fig. 1, it is possible to identify a number of stellar subcomponents, which can tentatively be identified with observed components in the Milky Way (see Samland & Gerhard 2003 for details). This is surprising, since no corresponding information was put into the simulation. (4) Because of the interplay between enrichment, feedback and dynamical collapse, the distribution of stars in the [Fe/H] - orbital eccentricity plane is surprisingly broad (Fig. 2). There does not exist a well-defined relation between these quantities for the model stars. The only significant difference to the observed distribution of Chiba & Beers (2000) is a lack of stars with metallicities [Fe/H] $\simeq -2$ on near-circular orbits.

Thus collapse models including cosmological infall and feedback from supernovae are considerably more complicated and can in some aspects be qualitatively different from traditional collapse models. Result (1) is clearly of relevance as regards the distribution of halo globular cluster ages. Results (2) and (4) are contrary to the predictions that are usually associated with the Eggen, Lynden-Bell & Sandage model.

Bekki & Chiba (2001) have published a one-phase model which in terms of the gas dynamics, star formation, and chemical enrichment description is much simpler than the model just described, and has no feedback, but which includes small-scale structure by imprinting a CDM power spectrum on the initial spherical matter distribution. In their model, substructure clumps form, and dissipationless processes such as dynamical friction and merging resp. disruption of these clumps are important. This has the effect of filling in the gap in the metallicity - eccentricity diagram of metal-poor halo stars on circular orbits (see their Fig. 13).

Based on these dynamical models, the idea of a hybrid formation for the Galactic halo looks promising. Within the broad class of hierarchical models, the dissipative collapse of a distributed gas component and the accretion of substructure is expected to occur simultaneously. From the results discussed
above, it appears possible that the right mixture of the two will in the end be able to explain the observed properties of the Galactic stellar halo. There is clearly still much work to do in finding out whether this assertion is true, and if so, what the right mixture is. By doing this work we will gain valuable insight into the galaxy formation process at large.

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Figure 1. Lower panel: distribution of stars in the metallicity-rotation velocity plane in the model of Samland & Gerhard (2003). Rotation velocities are perpendicular to the total angular momentum vector. Upper panel: metallicity distribution of all model stars, projecting along the rotation velocity axis. The dashed lines separate plausible subpopulations based on this diagram.
Figure 2. Stellar orbital eccentricities for a random sample of all stars in the model of Samland & Gerhard (2003), as a function of metallicity. The line shows the mean eccentricity as function of [Fe/H].