Galaxy Formation: One Star at a Time. New Information from the Kinematics of Field Stars in the Galaxy

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Abstract. We present a review of recent studies of the formation and evolution of the Milky Way galaxy, in particular based on large samples of non-kinematically selected stars with available proper motions. The Milky Way is argued to be a reasonable template for the formation of large spiral galaxies, the only one in which complete kinematical and abundance information can be readily obtained. Ongoing and future projects to obtain proper motions and spectral information for much larger samples of stars that will sharpen our perspective are discussed.

1. Introduction

Observational studies of galaxy formation often conjure visions of deep optical and infrared images of luminous baryonic material caught “in the act” at moderate to high redshift, perhaps inspired by the exquisite views provided in the Hubble Deep Fields. Although such data suggest that at least the basic outlines of a hierarchical assembly model most likely can be applied to many galaxies, the information content of these extremely faint smudges on the night sky is at present limited by the resolution and photon-gathering power of the largest telescopes. By taking the position that galaxy formation is best understood by detailed study of single galaxy, rather than by obtaining only the sketchiest knowledge of the ancient history of many galaxies, one is led to conclude that the optimal redshift for such studies is at $z = 0$, i.e., the present. We are speaking, of course, of our home galaxy, the Milky Way.

In some respects, we can think of the Milky Way as an analog computer simulation of the stages that many, if not most, large spiral galaxies must have passed through, from the epoch of collapse from the general expansion to the period of the first star formation, and the subsequent evolution leading to the “boundary conditions” that the Milky Way presents for modern observers. There are numerous clues to the early history of galaxy formation and evolution encoded in the motions and elemental abundances of individual stars in the Galaxy. The challenge to astronomers is to gather, and most importantly, to interpret, this information to provide constraints on the general patterns of (large) galaxy
formation throughout the universe. This approach is not without its limitations, of course. The Analog Milky Way V1.0 is a computer that:

- We live inside of
- Can only directly show us a small portion of the “program” at once
- We cannot re-boot
- Runs its “CPU” at speeds of Gyrs, not GHz!

Nevertheless, the Milky Way is the only galaxy for which we can (relatively) easily recover the full six-dimensional phase space information of position and velocity for a substantial number of its luminous constituents while simultaneously obtaining elemental abundance data for the same objects. Moreover, our ability to gather such information is sure to increase rapidly in the near future, with the completion of a number of full (or substantial) sky coverage photometry programs (e.g., 2MASS, SDSS), the continuation and extension of several ground-based astrometry programs (e.g., SPM, NPM, USNO), the successful operation of the next generation of astrometric satellites (e.g., FAME, SIM, GAIA), as well as the use of wide-field spectroscopic surveys for the inspection of large numbers of spectra of stars in the field of the Milky Way (e.g., 2DF and 6DF).

This conference was convened to discuss the broad issues of timescales in astrophysics. In the context of galaxy formation, this might be interpreted as the estimation of the ages of the oldest (and perhaps more importantly, the youngest) objects that might reasonably be assigned to the various luminous components of the Milky Way that we presently recognize – the halo, the metal-weak thick disk (MWTD), the bulge, the thick disk, and the thin disk. We suggest that the first step toward such a goal is to at least identify the proper order of formation of these components. In this brief review, we discuss how the kinematics and abundances of individual stars in a (still small) sample of well-chosen stars can be used to make a tentative inference. Many of the questions we seek to answer will only completely yield when much larger samples of stars with full information come available, but hopefully some of the techniques we explore will provide a good starting point.

2. Kinematic Studies – Past and Present

Kinematic studies of stellar populations in the Galaxy have long been limited by the availability of large samples of stars with measurements of:

- Velocities (radial and tangential)
- Distances (in particular, consistent determinations)
- Metallicities (accurate and consistent)

Such a database is required to constrain plausible scenarios for formation and evolution of the Milky Way. A number of the issues under current discussion include:
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- Measures of the local halo velocity ellipsoid and changes with Galactocentric distance
- The rotational character of thick disk and halo, and the existence of gradients in rotation velocity as a function of distance from the Galactic plane
- The existence of the MWTD, and the lower limit on its metallicity
- Correlations (or lack thereof) between orbital eccentricity and the metallicity of halo stars
- The global density structure of the halo population, and estimates of the axial ratios of the Galactic halo as a function of distance
- Searches for “kinematic substructure” in the halo
- Direct comparisons with simulations of galaxy formation

An ideal sample of stars for exploring these ideas would be unbiased in their selection with respect to both kinematic properties and abundances throughout the Galaxy. Although a number of projects have been initiated that will provide this sort of data (e.g., Morrison et al. 2000; Wyse et al. 2000), even an approximation of the ideal has not yet been achieved. Hence we must make a choice between introduction of:

- Kinematic bias: A tracer sample selected on the basis of stellar motions in the Solar neighborhood, e.g., the proper motion selected samples of Ryan & Norris (1991) or Carney et al. (1994)
- Abundance bias: A tracer sample selected to include stars with metallicities covering the range existing in the Galaxy \((-4.0 \leq [\text{Fe/H}] \leq 0.3)\)

We have chosen to place our emphasis on the latter, on the grounds that studies of the early formation history of the Galaxy must necessarily include stars of extremely low metallicity, even though they represent a relatively small fraction of the still-shining stars. In this sense an abundance bias is required in order to provide sufficient numbers of stars for meaningful investigation, in particular of the halo population.

The study of large non-kinematically selected stellar samples began in earnest with the literature assemblage of Norris (1986), who studied the kinematics of \(\sim 800\) stars with available radial velocities, distances, and abundances \([\text{Fe/H}] \leq -0.6\) (the upper cutoff being placed in order to exclude “spillover” from the far more numerous thin disk stars). Beers & Sommer-Larsen (1995) supplemented the Norris catalog with the inclusion of a number of stellar samples with measured radial velocities, distances, and abundances published in the literature in the intervening years (in particular from the HK survey stars of Beers, Preston, & Shectman 1992), finishing with a sample of \(\sim 1900\) stars. The catalog of Beers et al. (2000) extended the Beers & Sommer-Larsen assemblage to include additional stars, in particular RR Lyraes, and presented consistently determined estimates of distance and refined radial velocities and abundances for a total
sample in excess of ~2000 stars. Of greatest importance, however, was the addition of proper-motion information for over 50% of the cataloged stars, based on several new astrometric programs, including HIPPARCOS (ESA 1997), NPM (Klemola, Hanson, & Jones 1993), SPM (Platais et al. 1998), STARNET (Röser 1996), ACT (Urban, Corbin, & Wycoff 1998). Additional information is now available from the recently published Tycho–II catalog (Høg et al. 2000), but it is not considered in the discussion that follows. Figure 1 shows the spatial distribution of the stars in the Beers et al. catalog.

3. Results of the Chiba & Beers Analysis

Based on the large catalog of metal-poor stars with available proper motions, Chiba & Beers (2000) obtain full space motions for some 1200 stars. The local three-dimensional velocity components for this sample, \( UVW \), are shown in Figure 2 as a function of metallicity. This is the first time that such information has become available for an adequate number of low metallicity stars chosen without kinematic bias.

Inspection of panels (a) and (c) of Figure 2 suggests that there appears to be present a “core” of stars with \(-2.0 \leq [\text{Fe/H}] \leq -0.6\) that is drawn from a low-velocity-dispersion population, in addition to the usual high-dispersion halo population. This population is the MWTD, a component of the Galaxy that was first suggested by Morrison, Flynn, & Freeman (1990), and was the subject of debate in the literature for some time. Its presence now appears indisputable.
There are other pieces of evidence that strongly suggest the presence of a MWTD population. For example, Figure 3 is a comparison of the cumulative distribution of derived eccentricities for stars chosen in two abundance regimes, (a) for \([\text{Fe/H}] \leq -2.2\), and (b) for \(-1.4 < \text{[Fe/H]} \leq -1\). The different lines correspond to the cases when the range of \(|Z|\) is changed. Panel (a) shows that even at quite low abundance, roughly 20% of the stars have \(e < 0.4\). The cumulative distribution of \(e\) is unchanged when considering subsets of the data with a range of \(Z\), suggesting the absence of any substantial disk-like component below \([\text{Fe/H}] = -2.2\). By way of contrast, panel (b) shows that stars with intermediate abundances exhibit (a) a higher fraction of orbits with \(e < 0.4\) than for the lower abundance stars, (b) a decrease in the relative fraction of low eccentricity stars as larger heights above the Galactic plane are considered, and (c) convergence at larger heights to a fraction that is close to the 20% obtained for the lower abundance stars. These results imply that the orbital motions of the stars in the intermediate abundance range are, in part, affected by the presence of a MWTD component with a scale height on the order of 1 kpc.
Chiba & Beers obtain estimates of the local velocity ellipsoids of the halo and thick disk components:

- **halo:** $(\sigma_U, \sigma_V, \sigma_W) = (141 \pm 11, 106 \pm 9, 94 \pm 8) \text{ km s}^{-1}; [\text{Fe/H}] < -2.2$
- **thick disk:** $(\sigma_U, \sigma_V, \sigma_W) = (46 \pm 4, 50 \pm 4, 35 \pm 3) \text{ km s}^{-1}; -0.7 \leq [\text{Fe/H}]$

Progressing from higher to lower abundances, the velocity dispersions gradually increase as one transitions from disk-like to halo-like behavior. Under the assumption that the MWTD population shares a common velocity ellipsoid with the higher abundance thick-disk stars, a mixture model analysis suggests that, in the Solar neighborhood, the MWTD contributes about 30% of the metal-poor stars in the abundance range $-1.7 < [\text{Fe/H}] \leq -1$, and perhaps only 10% below $[\text{Fe/H}] = -1.7$. It should be recalled, however, that the sample of stars selected by Beers et al. (2000) were contributed primarily from objective-prism surveys that generally placed a lower cut on Galactic latitude of $|b| > 30^\circ$. Hence, the above fractional contributions of the MWTD at intermediate abundances should be viewed as lower limits on the actual fraction. Indeed, a recent analysis of nearby metal-weak giants selected with $|b| < 30^\circ$ suggests that the fraction of MWTD stars at abundances $[\text{Fe/H}] \leq -1.7$ may be closer to $\sim 40\%$ (Beers et al. 2001), much higher than the previously inferred value. Clearly, data obtained from surveys that also target lower Galactic latitudes are needed to resolve this quandry (e.g., Wyse et al. 2000).

Figure 4 is a plot of the mean rotational velocity $< V_\phi >$ as a function of $[\text{Fe/H}]$ for stars selected from several cuts in distance above or below the Galactic plane. The general decline in rotation speed with decreasing $[\text{Fe/H}]$ marks the transition from a disk population (at the high abundance limit, the canonical thick disk, at the low end, the MWTD) to a halo population. A “break” at $[\text{Fe/H}] \sim -1.7$ is evident in all three cuts in Z. However, note that below this metallicity, the rotational character of the cuts seem to differ. This feature arises because, close to the Galactic plane, the halo population exhibits a rather strong vertical rotational velocity gradient $\Delta < V_\phi > /\Delta |Z| = -52 \pm 6 \text{ km s}^{-1} \text{ kpc}^{-1}$. A smaller, but still significant, gradient appears present in the thick-disk stars as well, $\Delta < V_\phi > /\Delta |Z| = -30 \pm 3 \text{ km s}^{-1} \text{ kpc}^{-1})$. The presence of such gradients is a signature of dissipational collapse in both populations.

Before closing this brief summary, it is interesting to view the entire distribution of orbital eccentricities for the stars analysed by Chiba & Beers (2000). Inspection of Figure 5 leaves little doubt that there exist metal-poor stars with eccentricities that populate the entirety of the diagram. This result stands in rather stark contrast to previous claims of an existence of a strong correlation between orbital eccentricity and metallicity (dating back to the classic paper of Eggen, Lynden-Bell, & Sandage 1962) that based their initial selection of stars on high proper-motion surveys.

4. **Reconstruction of the Halo Density Profile from Local Kinematics**

A number of authors have followed up the pioneering work of May & Binney (1986), who pointed out that an application of Jeans’ theorem might enable the reconstruction of the global structure of the stellar halo from kinematic
Figure 3. Cumulative $e$ distributions, $N(<e)$, in the two abundance ranges (a) $[\text{Fe/H}] \leq -2.2$, and (b) $-1.4 < [\text{Fe/H}] \leq -1$. The thick solid, thin solid, dashed, and dotted histograms denote the stars at $|Z| \geq 0.0$ kpc (all stars), $|Z| \geq 0.5$ kpc, $|Z| \geq 1.0$ kpc, and $|Z| \geq 1.2$ kpc, respectively.

information of a reasonably large sample of local halo stars. This technique relies on the fact that halo stars that are presently found within a few kpc of the Sun have, during their past motions, explored a substantial fraction of the complete phase space of position and velocity in the Galaxy. Sommer-Larsen & Zhen (1990) developed a maximum-likelihood methodology for the implementation of this idea, and applied the technique to a sample of 118 nearby halo stars with $[\text{Fe/H}] \leq -1.5$. Most recently, Chiba & Beers (2000) have applied the method to a sample of 359 stars with $[\text{Fe/H}] \leq -1.8$ located within 4 kpc of the Sun.

Figure 6 shows the reconstructed density profile of the halo obtained by Chiba & Beers, compared to that derived by Sommer-Larsen & Zhen, plotted as a function of distance along the Galactic plane, $R$. The density distribution for $R > 8$ kpc is well described by a power-law profile $\rho \propto R^{-3.55 \pm 0.13}$, similar to that obtained by Sommer-Larsen & Zhen except in the outermost region, where the more recent analysis does not show a fall-off (likely due to the smaller number of stars considered previously). This result is quite similar to previous estimates of the halo density profile based on counts of globular clusters (Harris 1976;
Figure 4. Distribution of the mean rotational velocity $< V_\phi >$ vs. [Fe/H] for stars closer than 4 kpc from the Sun, assuming an LSR rotation velocity of 220 km s$^{-1}$. Filled circles, crosses, and open circles correspond to the stars at $|Z| < 4$ kpc, $|Z| < 1.6$ kpc, and $|Z| < 1$ kpc, respectively.

Zinn 1985), and field horizontal-branch and RR Lyrae stars (Preston, Shectman, & Beers 1991, and references therein). Note that the fall-off in reconstructed density for $R < 8$ kpc is an artifact arising from the lack stars in the Solar neighborhood that explore the inner regions of the Galaxy.

A different view of the reconstructed halo is presented in Figure 7a, where contours of constant density are plotted in the $(R, Z)$ plane. The appearance of this figure is quite suggestive. For the outer part of the halo, $R > 15$ kpc, the contours appear roughly spherical, while those in the inner halo become increasingly flatter with declining distance. A more quantitative estimate of this behavior, based on the derived axial ratio of the reconstructed halo as a function of distance, reveals that the density distribution in the outer part of the halo, $R \sim 20$ kpc, is quite round. The axial ratio $q$ appears to decrease with decreasing $R$ over $15 < R < 20$ kpc, and the inner part, at $R < 15$ kpc, exhibits $q \sim 0.65$. Similar results, obtained by completely different methods, were found by Preston et al. (1991) and Morrison et al. (2000). Thus, the present stellar halo can be described as nearly spherical in the outer part and highly flattened in the inner part.

Chiba & Beers (2001) extended this type of analysis to investigate the structure of the Galactic halo at a time before the disk had a chance to form. Since the bulk of halo stars are found in the inner portion (owing to the large exponent in the density profile), where the gravitational potential arising from a disk dominates over that of the halo, the present-day halo might have had its observed structure affected to a large degree by later disk formation. Chiba & Beers studied the changes in the derived orbits of their sample of stars when
Figure 5. The relation between [Fe/H] and $e$ for 1203 non-kinematically selected stars with [Fe/H] ≤ −0.6. Note the diverse range of $e$ even at low metallicities.

the potential associated with a disk is slowly removed from their model, then reconstructed the density profile of the halo population after it was completely absent. Their result is shown in Figure 7b. The density contours in the (past) inner halo are substantially rounder than inferred for the present halo. The axial ratio obtained for the pre-disk halo is approximately $q = 0.8$ for $R \leq 15$ kpc, transitioning to spherical for $R \sim 20$ kpc. These results suggest that the presently flattened inner halo is a consequence of both an initially slightly flattened inner distribution that has been further flattened by later formation of a disk structure. An initially flattened halo is a signpost of early dissipative formation of this component of the Galaxy.

5. Evidence for Halo Substructure

Several studies (e.g., Helmi et al. 1999; Chiba & Beers 2000) have presented evidence for the existence of kinematic “clumping” of halo stars, a result that is expected if a hierarchical assembly of the Galactic halo applies. Though the numbers of stars in the recognized or suggested structures is presently quite small, we anticipate that future (much) larger data samples will demonstrate further evidence of the phenomenon. Indeed, one of the first exciting results from the SDSS reveals extensive spatially coherent structures of field horizontal-branch and halo blue straggler stars, apparently associated with the trail(s) of debris left by the Sagittarius dwarf (Yanny et al. 2000; Ibata et al. 2001). It should be noted that searches in angular momentum space (obtainable for
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Figure 6. Density distributions of the reconstructed halo in the Galactic plane, for $\text{[Fe/H]} \leq -1.8$ (filled circles) and $-1.6 < \text{[Fe/H]} \leq -1$ (open circles). Both plots have been shifted arbitrarily along the vertical axis. The dotted line denotes the power-law model with exponent $\beta = -3.5$. For comparison, the density distribution based on the Sommer-Larsen & Zhen (1990) sample with $\text{[Fe/H]} \leq -1.5$ is shown as crosses.

Stars with full space motions are inherently much more sensitive than searches based on spatial association (Helmi & White 1999), so efforts to expand the numbers of stars with measured proper motions are of particular value. Studies of the elemental compositions of stars associated with the identified kinematic structures (Ivans et al. 2001) will help to establish if a “chemical signature” (such as low alpha-elements) can be assigned to the process.

6. Insights from Numerical Simulations

The hypothesis of the dissipative formation of the inner flattened halo, as well as the later accretion of satellites onto the outer halo, is a natural consequence of the cold dark matter hierarchical clustering model (Bekki & Chiba 2000; 2001). This model postulates that a protogalactic system initially contains numerous subgalactic clumps, comprised of a mixture of primordial abundance gas and dark matter. Once star formation initiates in these clumps, the energy associated with Type II SN explosions quickly drives the gas out into the general ISM of a still-forming galaxy, at the same time touching off formation of “second-generation” metal-poor stars in the dense shells of these supernovae, as in the models of Tsujimoto, Shigeyama, & Yoshii (1999). The low-mass stars
formed in this way are the long-lived fossils we now can observe at extremely low metallicity. Mergers of these small clumps, now composed of dark matter and second-generation stars (but no gas), takes place in a dissipationless manner.

Once the (enriched) gas that was expelled by early supernovae cools, it will fall back into the ever-more massive clumps. In the simulations of Bekki & Chiba, these larger clumps move gradually toward the central region of the system, due to both dynamical friction and dissipative merging with smaller clumps. Finally, the last merging event occurs between the two most massive clumps, and the metal-poor stars formed inside the clumps are disrupted and spread over the inner part of the halo. The aftermath is characterized by a flattened density distribution. Some fraction of the disrupted gas from the clumps may settle into the central region of the system, and produce a more enriched, more flattened density distribution, providing the “raw material” for the formation of the Galactic bulge and thick disk. Some of the initially small density fluctuations in the outer region would have gained systematically higher angular momentum from their surroundings, and then slowly fall into the system after most parts of the Galaxy were formed. This may correspond to the process of late satellite accretion, contributing primarily to the outer part of the halo.

Thus, the reported initial state of the stellar halo can be explained, at least qualitatively, in the context of a hierarchical clustering scenario.

7. Order of Formation of the Observed Luminous Components of the Galaxy

The picture that emerges from the observations and simulations is one in which the oldest stars that are presently observable in the Milky Way might be found
in any of several recognized components. In this interpretation, the inferred order of the formation of the components of the Milky Way is expected to be:

- Inner halo
- Metal-weak thick-disk
- Thick disk and Galactic bulge
- Thin disk

All the while, the presently observed outer halo is in the process of formation.

We conclude that searches for the most metal-poor (and ancient) stars to be found in the Galaxy should be concentrated on the inner halo. This component is expected to harbor the largest relative fraction of second-generation stars. However, it should be noted that the correlation between metal abundance and age is expected to be extremely weak, even for the most metal-deficient stars. The enrichment history of the early Milky Way is driven primarily by the efficiency of star formation during the complex early epochs.

In order to test the ordering suggested above, it is more revealing to consider the youngest stars that might be associated with a given observed component of the Galaxy, thus obtaining information on when star formation ceased in that component. Because the second-generation stars share a common origin (in the shells of supernovae exploding in the first clumps of dark matter and primordial gas), and then are re-distributed by subsequent collisions of clumps, representatives of such stars might be found in all but perhaps the thin disk of the Galaxy.

8. The Importance of Future Spectroscopic and Astrometric Surveys

There are several factors that limit to our ability to read back the history of the formation of the Milky Way based on present data. The “resolution” of our vision is severely limited by the (still) relatively small numbers of stars that are presently known with $[\text{Fe/H}] \leq -2.0$. The $\sim 1000$ stars below this abundance limit that are currently recognized may appear to be a sufficiently large number, but not when one is attempting, as we have, to reconstruct the density structure of the early Galaxy from the phase space of position and velocity that these stars explore. Surveys that efficiently identify much larger numbers of extremely metal-poor stars have recently been completed, but are only now starting to be exploited to reveal the riches they contain (e.g., the stellar component on the Hamburg/ESO survey, see Christlieb & Beers 2000 for a comparison of this survey with the HK-I survey, and the HK-II survey, Rhee, Beers, & Irwin 1999; Rhee 2000). It should also be recognized that stars of intermediate abundance, $-2.0 \leq [\text{Fe/H}] \leq -1.0$ are crucial for study of the MWTD-halo interface, and for that reason, are deserving of attention as well. Progress relies on the assignment of telescope time to medium-resolution follow-up surveys, either with rapid single-star measurements with 4m-class telescopes or with multi-fiber, wide-field measurements with instruments such as the 6DF on the UK-Schmidt telescope (Watson et al. 2000).
Even after these stars are recognized, and have had their radial velocities and metallicities measured, there still remains the need for determination of accurate proper motions and (eventually, from astrometric satellites to be launched in the coming decade) accurate distances. Only then will the complete vision be realized.

What can be done in the meantime? In recent years, until funding cuts terminated progress, the most accurate ground-based proper-motion measurements of the stars that occupy the MWTD and halo of the Galaxy have come from the SPM, the Southern Proper Motion survey (e.g., Platais et al. 1998). A proposal to renew the SPM is currently under review at the (US) National Science Foundation. If this proposal is funded, the path is clear for the determination of proper motions, as well as accurately calibrated V magnitudes and $B - V$ colors, for the $\sim 10,000$ metal-poor (and $\sim 30,000$ field horizontal-branch and halo blue-straggler) stars in the southern sky identified by the HK-I, HK-II, and Hamburg/ESO surveys, at least several years before the first data return from future astrometric missions. With this data in hand, astronomers will be able to refine the issues they might hope to explore with the wealth of data from the astrometric satellites.

We can, and hopefully will, be able to understand the complex process of galaxy formation and evolution for at least ONE galaxy, our home, the Milky Way. Unless the universe is perverse, what we learn in this process will apply to many, if not most, large spiral galaxies.

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