Part 4. Galactic Structure

FORMATION AND EVOLUTION OF THE MILKY WAY

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1. Introduction

To paint with broad brush strokes, the spectrum of Galactic formation models has as extrema what may be termed the "fast and smooth" and the "slow and lumpy" scenarios. Appropriate or not, to ascribe as champions of these views the works of, respectively, Eggen *et al.* (1962, ELS hereafter) and Searle & Zinn (1978, SZ hereafter) has become *de rigueur*—though it is prudent to bear in mind the soft focus of historical perspective, and the maxim that "no one remembers what one has said, only what others say one has said" (on this point, see Sandage 1990 and Majewski 1993, section 1). If recently published textbooks (whose task is to relay pedantically what the experts have said) mirror our present understanding of the formation of the Milky Way, then it would seem that the experts have done little to negotiate the different formation pictures to offer a coherent compromise:

> [Figure 18.24 shows the] schematic sequence of the collapse and condensation of a large cloud of gas and dust to make globular clusters and the Galaxy's disk. Because of its original spin, the matter eventually makes a disk with a central bulge. *The stars in the globular clusters form in the cloud before the disk had developed. The entire process took less than one billion years.* [Zeilik 1996].
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> Astronomers reason that, early on, our Galaxy was rather irregularly shaped, with gas distributed throughout its volume. *Possibly it formed via the merger of several systems, as depicted...* When the stars formed during these stages, there was no preferred direction in which they moved and no preferred location in which they were found. *In time*, rotation caused the gas and dust to fall to the Galactic plane and form a spinning disk... *The older stars were left behind, forming the halo...* New stars forming in the disk inherit its overall rotation and so orbit the Galactic center on ordered, circular orbits. [Chaisson & McMillan 1996].

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These elementary descriptions (emphases mine) touch on some of the concepts typically allied to the "fast and smooth" scenario—*e.g.*, fast collapse and Galactic "spin-up" during collapse, abundance gradients between and within Galactic populations, and relatively smooth (*i.e.*, "organized" or sequenced) spatial, kinematical and chemical transitions between populations—as well as notions often coupled to the "slow and lumpy" model—namely, an extended (halo) configuration, unorganized kinematically and chemically, born of the merger of initially isolated systems. The theme of this brief is that our understanding of the Galaxy may not be nearly as confused as the above synopses would imply; progress is being made toward a description which, not surprisingly, is a compromise of the extreme models often proffered. This is not to say that a universally accepted formation scenario exists; however, recent observational successes have yielded a number of important, previously missing, pieces to the puzzle. At the simplest level, the surfacing compromise involves a "slow and lumpy" scenario for the extended parts of the Galaxy, referred to here as the "halo," with aspects of the "fast and smooth" paradigm reserved for the interior regions of the Galaxy, the thin and Intermediate Population II (IPII), "thick" disks.

I conclude with an appeal to large, systematic surveys as the promise toward resolving the perplexities of Galactic structure and formation.

2. A Slow Formation for the Halo

Accurate relative age dating of star clusters is perhaps one of the most important products of the CCD photometry age. The result of this work is clear evidence for a rather protracted formation epoch for globular clusters (even excluding the so-called "disk" globulars). Whatever the absolute value for the *mean* age of the globular clusters (a topic still of some considerable debate), it is clear that the globular cluster age dispersion is substantial—at least several Gyr, but in any case much larger than a "rapid" collapse scenario would imply. The bevy of "rogue" clusters of youthful age (2–4 Gyr less than the mean cluster age) is now large enough (Rup 106, Pal 12, Ter 7, N6366, Arp 2, IC4499; see Gratton & Ortolani 1988, Stetson *et al.* 1989, Buonanno *et al.* 1993, 1994, Da Costa *et al.* 1992, Da Costa & Armandroff 1995) that they can no longer be considered exceptional cases, but rather they represent an important aspect of Milky Way construction.

Even more startling a threat to old paradigms is that while the age spread of halo globular clusters widens, so too does the age spread of open clusters (Janes & Phelps 1994) and other "disk" populations. The result is a growing disk/halo age overlap that breaks down the traditional view of a distinct "age of halo formation" followed by an "age of disk formation." The age of the open cluster Be 17 is now given as 12^{+1}_{-2} (Kałużny 1994, Phelps 1997). Though subject to vagaries of absolute age scales, through relative age dating schemes (Janes & Phelps 1994) it is clear that this object is *older* than the youngest halo globular clusters. The latter are older than 47 Tuc, the prototypical "disk" globular cluster. Coupled with this blurring in distinctive ages is a blurring of the distinction between "globular" and "open" clusters; several objects, *e.g.*, Lyngå 7 (Ortolani *et al.* 1993) and BH176 (Kałużny 1995) may be "transitional" between the two cluster types.

An upper age for the disk similar to that provided by the open clusters is also yielded by Strömgren photometry studies of disk field stars (Edvardsson *et al.* 1993, Nordström *et al.* 1996), as well as the results of combining the most recent white dwarf luminosity functions with the latest white dwarf cooling theory (Hernanz *et al.* 1994, Isern *et al.* 1995, 1997).

It is now evident that halo globular clusters were forming even after the Galactic disk had initiated star formation. This provokes the vexing question of the location of the formation sites for the young halo globular clusters (Section 3). Relevant to this question is the fact that, when divided into "young" and "old" halo globular groups (on the basis of their horizontal branch morphology, *i.e.*, those exhibiting the most significant second parameter effect), distinctively different chemical, kinematical and spatial distributions obtain. The "young" halo clusters have more extreme kinematics, are distributed in an extended, spherical distribution, and exhibit no metallicity gradients, while the "old" clusters as a group exhibit less extreme kinematics and are distributed in a flattened configuration (van den Bergh 1993, Zinn 1993a, Da Costa & Armandroff 1995; see also the earlier work of Rodgers & Paltoglou 1984). The "old halo" globular clusters and their apparently natural extension into the disk globulars, when arranged according to [Fe/H], *do* demonstrate kinematical and spatial gradients reminiscent of the ELS "spin-down" concept (Zinn 1993). It has been suggested (Zinn 1993) that the disk+old halo globulars may trace the spin-down of a single, dissipational the Galactic disk. Similarities between properties of this latter set of globulars and those of the Galactic IPII suggest they represent the same Galactic population (Majewski 1993, 1995; Section 5).

On the other hand, the null or retrograde mean velocity of the "young halo" globulars, their lack of an [Fe/H] gradient, and their spatial distribution are inconsistent with their formation as part of a grand collapse that may have formed the inner Galaxy. Coupled with their apprently younger ages, an origin tied to accretion is implied, along the tenets of the SZ scheme. If the "old halo+disk" component represents some form of grand collapse of a primordial (but eventually self-enriching), Galaxy-sized gas cloud, the *later* formation of some "young halo" globulars requires a reservoir of gas that did not participate in the collapse, but either left behind in, or introduced into, the outermost parts of the early Galactic system.

3. The Role of the Galactic Satellites and High Velocity Clouds

Maps (*e.g.*, Wakker 1991a) of the H I high velocity clouds (HVCs) make evident two points, *assuming that the HVCs are at large distances and not associated with the Galactic plane*: (1) There is H I in the halo now. Though presently meager on galactic mass scales, the presence of *any* such gas at the present stage of Galactic evolution encourages contemplation of previously larger, available reservoirs. (2) If represented by the distribution of this gas, the halo is "lumpy" now. Murphy *et al.* (1995) find 37% of lines of sight to have high velocity H I with $N_{\mathrm{H}} = 7 \times 10^{17}$ cm^{-2}. Much of this is concentrated into large, often elongated complexes, like the Magellanic Stream and Complexes A, M and C. Unfortunately, there is still only minimal data bearing on the distances to the HVCs, but the weight of evidence seems to support cloud distances (especially when coupled to their velocities) commensurate with halo membership for HVCs (Danly 1989, Danly =it et al. 1993, de Boer *et al.* 1994, Keenan *et al.* 1995, Wakker *et al.* 1996).

Are the HVCs primordial clouds left *in situ*? The gas metallicity is low but highly variable from complex to complex—*e.g.*, 0.002 to $>$ 0.07 the solar value for Ca^{+}/H I (but these measurements are subject to many uncertainties, such as net exchange with dust; Schwarz *et al.* 1995). The general conclusion is that this gas cannot be *entirely* primordial (Schwarz *et al.*; Wakker 1991b gives a more complete treatment of HVC origin scenarios).

Was this gas stripped out of Galactic satellites? The stringy appearance of the various complexes is reminiscent of the Magellanic Stream, which is generally accepted to represent gas pulled out of the Magellanic system. There are some intriguing correlations between the orientations of these HVC chains and aligned families of Galactic satellites, such as the proposed "Magellanic" and "Fornax-Leo-Sculptor" planes (Kunkel 1979, Lynden-Bell 1982). The additional correlation of second parameter globular clusters to these planes (Lynden-Bell 1982, Majewski 1994, Lynden-Bell & Lynden-Bell 1995, Fusi Pecci *et al.* 1995) as well as the increasing evidence for tidal disruption of satellites (see below), suggests closer cosmogonical ties between satellite galaxies, young halo clusters, halo field stars and HVCs should these spatial correlations prove more than chance. Kinematical data will be essential to testing this hypothesis. For example, a simple accounting of the presently restricted distribution of the statistical phase space {spatial position, radial velocity, proper motion estimated from orientation} by Kunkel *et al.* (1997) suggests an original population of 10^3–10^4 dwarf galaxies; since observational evidence for even short look-back times does not support such large overpopulations, Kunkel *et al.* propose that tidal disruption of formerly larger satellites may have spawned an abundance of débris particles populating a small portion of their statistical phase space. Analysis of the growing number of absolute proper motions for Galactic satellites shows a remarkable coincidence between the orbits of the Magellanic Clouds, Ursa Minor and Draco, and consistent with a trailing Magellanic Stream in the common orbital plane (see Majewski *et al.* 1997); however, recent evidence is less supportive of the Fornax-Leo-Sculptor alignment of satellites (Majewski *et al.* 1997) and clusters (Dauphole *et al.* 1996). The discovery (Mirabel *et al.* 1992) of dwarf galaxies forming in the tidal débris of interacting galaxies provides an especially relevant paradigm to consider in the context of these possible alignments.

Another obvious location for post-collapse halo gas reservoirs is in the dwarf satellites themselves. As a group, they demonstrate a remarkable age spread, even excluding the presently gas-rich Magellanic system. Apart from Sagittarius (Sgr), all of the satellite dSph's contain old stellar populations, but half of them also have evidence for intermediate-aged populations, as young as 8–10 Gyr old in Leo II (Mighell & Rich 1996) and ≈ 6 Gyr old in Carina (Smecker-Hane *et al.* 1994). Star formation histories are clearly varied from satellite to satellite. For example, Carina shows evidence for distinct star formation bursts whereas Leo II had an extended star formation phase wherein most of the stars formed throughout a 6–8 Gyr period. The individual nature of this star formation leads to interesting complexities, such as the fact that Carina has two stellar populations with different ages but about the same [Fe/H], whereas Sgr has two populations with the same age but different [Fe/H] (Sarajedini & Layden 1995).

The existence of multiple star generations in individual dSphs raises the question of how such small galactic systems sustain a major burst of star formation, yet retain enough gas to instigate a succeeding burst? The answer may be related to the apparently large mass-to-light ratios suggested by internal velocity dispersions, though it is clear that a high M/L explanation for (at least some of) the high velocity dispersions is still disputed by tidal model enthusiasts (Kuhn *et al.* 1996, Burkert 1997; see Pryor 1996 and Irwin & Hatzidimitriou 1995 for recent advocations to the dissenting viewpoint). The possibility of some kind of pressure confinement is raised by recent results of Weiner & Williams (1996), whose detection of Hα emission on the leading edges of three major H I clouds in the Magellanic Stream suggests the presence of a large density, $n_{\rm H} \approx 10^{-4}$ cm^3, of hot, ionized gas at large distances from the Galaxy. (Note that Moore & Davis 1994 argue for such a hot gas phase based on the present configuration and dynamics of the Magellanic Stream.) These results also support a ram-pressure stripping origin, rather than a tidal origin, for the Magellanic Stream.

4. More Lumpy Structure in the Halo

The above comments on the origin of the Magellanic Stream notwithstanding, it is now clear that tidal intreractions do play a role in the formation of the Galactic halo. The example of the tidally disrupted Sgr dwarf galaxy (Ibata *et al.* 1995) confirms earlier suspicions that the destruction of Galactic satellites contributes both clusters and stars to the halo milieu. Satellite mergers should leave behind fossil evidence in the form of phase space substructure for field stars. Tidally disrupted stellar systems produce long-lived, coherent streams of stars strung out along the orbit of the decaying parent object (see models in McGlynn 1990, Moore & Davis 1994, Johnston *et al.* 1996), analogous to the streams of meteroid débris left along the paths of comets orbiting (and slowly destroyed by) the sun. To the extent that mergers contribute to the formation of the halo dictates whether tidal streams are an extra signature overlaying a dynamically relaxed stellar population (formed by other processes), or whether the halo has a more complex structure, like "a can of worms" (Majewski *et al.* 1996b).

Eggen (cf. 1996a,b and references therein) has long championed the idea of the existence of moving groups of metal poor, high velocity stars in the solar neighborhood. Other evidence for halo phase space substructure has been hinted at by various tentative findings of possibly more distant halo moving groups (see references in Majewski *et al.* 1996a), typically manifested as unexpected clumpings in position and radial velocity in *in situ* surveys of halo stars. That the Sgr dwarf was discovered in a similar way, albeit with much greater statistical significance, suggests a logical connection between these moving groups and disrupted dwarf satellites; presumably the less significant "detections" of radial velocity groups reported by others correspond to older, now more tenuous, tidal streams.

We (Majewski *et al.* 1994, 1996b) have been investigating evidence of apparent phase space substructure in a deep survey of stellar proper motions, photometry and spectroscopy towards the North Galactic Pole (SA57). Proper motion data alone (Majewski 1992) gave rise to the unexpected result that stars beyond about 5 kpc from the Galactic plane (the distance at which the IPII stellar density drops off sufficiently that the halo dominates) showed a significant mean *retrograde* rotational velocity. This alone is problematical for grand collapse scenarios for the halo, and implies a significant contribution of halo stars formed in some other way. Among the retrograde stars, Majewski (1992) identified a candidate halo "moving group," which subsequent spectroscopic analysis has supported by way of independent coherence in the group radial velocities. Full velocity information for stars in this magnitude-limited survey reveals, moreover, that the halo appears to contain a high degree of dynamical clumpiness: very few halo stars in the SA57 sample do *not* appear to belong to one of several, relatively distinct velocity clumps. This evidence suggests a dynamically young, *lumpy* structure for the halo, which may be *dominated* by the débris of tidally disrupted stellar agglomerations, either globular clusters or dwarf satellite galaxies, which *slowly* (over a Hubble time) have been dissolving into the "melting pot" that is the stellar halo.

5. The Division of Old Stellar Populations

Distant halo stars, many kpc from the Galactic mid-plane, exhibit extreme kinematics with significant phase space substructure that suggests an origin by way of, and perhaps dominated by, accretion events (Majewski *et al.* 1996b). At the same time, the IPII or "extended"/"thick" disk shows evidence of being a ubiquitous, vertically extensive, yet still predominantly flat, structure, and it contains both extremely metal-poor stars and stars that rotate more slowly with increasingly larger distances from the Galactic plane (in the interest of brevity, the reader is referred to Majewski 1995 for references supporting these statements). Therefore, it is useful to consider a new description of Galactic field star populations that parallels Zinn's division of the Galactic globular cluster system into: 1) a "younger," spheroidally distributed population that is non- or retrograde rotating and with an origin possibly tied to accretion processes; and 2) an "older," flattened distribution showing ELS "spin-up" and with a origin possibly related to dissipational collapse. Such a paradigm for both globular clusters and stars provides not only economy of hypothesis, but simultaneously resolves a number of various Galactic survey results previously considered inconsistent with one another (see Majewski 1993).

This physical description of stellar chemical, spatial and kinematical distributions points to a model of stellar origins that essentially represents a marriage of the SZ and ELS models. There appear to be (Sandage 1990, Majewski 1993) two populations of older, metal poor stars in the Galaxy: one closely aligned with traditional notions of a more or less spherically distributed, kinematically extreme Galactic "halo," but now associated with an *accreted*, SZ-like formation; and a second population with spatial and kinematical properties usually reserved for the Galactic IPII, or "extended"/"thick" disk population, but having an origin more along the lines of the global collapse envisioned by ELS (albeit on a slower, dissipational timescale). The connection or independence of the latter population to the Galactic "thin" disk is still a subject of great controversy; however, a number of lines of evidence support a similarly elderly age for both the thin disk and IPII (Section 2; references in Majewski 1995). Subsequent discussions of these new "dual halo" Galaxy scenarios refer to the two old, metal-poor populations, respectively, as the "accreted" and "contracted" halo (Norris 1994), or the "high" and "low" halo (Carney *et al.* 1996).

6. What's Old is New Again: Systematic Surveys of the Galaxy

At the turn of this century, Kapteyn (1906) devised the *Plan of Selected Areas* ("SAs") as a means to "attack" systematically the problem of understanding "the sidereal world," *i.e.*, the Milky Way system. There ensued a period of great activity, whereby substantial amounts of effort the world over was devoted to contributing photometry, astrometry, and spectroscopy of stars in Kapteyn's 206 SAs. The grand scope and initial perceived importance of the *Plan* was such that coordination was essential, and this prompted the eventual creation of *IAU Commission 32: Selected Areas* as well as the *Subcommittee on Selected Areas of IAU Commission 33: Structure and Dynamics of the Galactic System.* Coordination of the *Plan* was also the subject of two of the earliest IAU Symposia (Nos. 1 and 7).

Since the mid-part of this century—when it was discovered that the spiral nebulae were extragalactic systems, and also coincident with the rise in emphasis on star *clusters* as a tool for Galactic astronomy (Paul 1981)—activity on the SAs has unfortunately strongly declined (IAU Comm. 32 no longer exists). However, the wisdom and value of a systematic and coordinated astrometric, photometric and spectroscopic approach to studying the Milky Way is now more obvious. There is growing evidence that various subsystems of the Galaxy (*e.g.*, the bulge with its bar, the disk with its warp, and the apparently dynamically unrelaxed halo with its gaseous and tidal, stellar streams) are highly assymmetric, and therefore not described adequately by global models derived from only a few lines of sight (a common practice). Kapteyn's original vision of a fully integrated photometric, astrometric and spectroscopic survey has never been fully realized, though the decline in SA activity has overlapped with the development of modern instrumentation that might be brought to bear on the program with far more efficiency, precision and depth than he could have imagined.

To be sure, forays along this path are being made (for example, those by the Basel group, *e.g.*, Fenkart 1989; Sandage 1983; the Besancon group, *e.g.*, Ojha *et al.* 1996; and by the author and collaborators, *e.g.*, Siegel *et al.* 1997), but a satisfactory Galactic stucture "solution" may not be possible without a grand, all-out, "full-sky" attack as Kapteyn envisioned. Such systematic optical surveys of field stars will need to be integrated both with complementary work on Galactic clusters and satellites, as well as information at other wavelengths on the gaseous phases of the Milky Way: *e.g.*, X-ray surveys will provide necessary constraints on/checks for diffuse, ionized gas, while much more work is needed to understand the relationship of the H I radio data, especially the HVCs, to the stellar populations of the Milky Way and its satellite system. Ultimately, all of these Galactic studies will need to be combined with similar studies of external galaxies before a satsifactorily complete picture of the formation and evolution of normal, Milky Way-like galaxies can be obtained.

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