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GALACTIC STRUCTURE SURVEYS AND THE EVOLUTION OF THE MILKY WAY

S. R. Majewski[1]

The Observatories of the Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, California 91101

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INTRODUCTION

Much of galactic research is directed at the determination of those global properties of stellar populations that bear directly on models of formation. This review investigates the evolution of the Milky Way from the perspective afforded by surveys of Galactic stellar populations. I concentrate primarily on the most commonly-measured stellar parameters in systematic Galactic surveys of stars or star clusters: 1. location with respect to the Galactic center[2], 2. velocities and velocity dispersions[3], 3. metallicity, defined as [Fe/H], and 4. age. As the point of departure, focus will be placed on a family of "key observables"—specific, testable correlations within this parameter space that constrain the Galactic formation

[1]Hubble Fellow.

[2]Referred to in cylindrical coordinates (r, θ, Z), and where the Galactocentric distance is given by $R^2 \equiv r^2+Z^2$ and the Sun's distance is $r_{\odot} = R_{\odot} = 8.5$ kpc.

[3]The corresponding velocities with respect to the local standard of rest (LSR) are denoted (U, V, W), where U is positive in the direction of the Galactic anticenter, V (also known as the Strömberg asymmetric drift) is positive in the direction of Galactic rotation, and—assuming a 220 km s^{-1} velocity for the LSR—is related to the rotational velocity as $V = V_{rot} - 220$ km s^{-1}, and where W is positive towards the North Galactic Pole (NGP).

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models—and generally restricted to a cross-sectional view along Z at $r_{\odot}$. Thus the Galactic bulge is not addressed here (see reviews by Frogel 1988, Rich 1992), and the detailed chemical evolution of the Galaxy is only briefy visited (Sections 3.2.2 and 3.4.3; see reviews by Wheeler et al 1989 and Rana 1991). For clarity, some topics have been subdivided into separate treatments of individual Galactic components, but note that such partitioning may be semantic for evolution models that advocate a more continuous connection of populations. With no pejorative intent, the term "Intermediate Population II," IPII hereafter, has been adopted for that structure which has been variously referred to as the "thick disk," "extended disk," "high velocity disk," and "flattened" or "inner spheroid" since these terms are often identified with specific formation scenarios and I wish to indicate no initial predilection for one or the other. The term "Intermediate Population II" is more neutral as well as being the original nomenclature used for this structure, as presented at the 1957 Vatican Conference on Stellar Populations (O'Connell 1958). "Intermediate" refers to its kinematical and abundance distributions, which appear to fall between the extremes of the halo and thin disk populations. The term "thin disk" is used to refer to the structure of scaleheight $h_z = 350$ pc, since use of the term "old disk" can be misleading: IPII may, in fact, be an older disk component than the "old disk."

Section 1 of this article reviews models of Galaxy formation and outlines their predictions for the key observables, with particular focus on mechanisms for creating IPII. Section 2 reviews the building blocks of Galactic structure surveys. Potential sources of selection bias, systematic error, and other subtleties that may have contributed to disparate measurements of the key observables among different surveys are considered. The key observables are explored in depth in Section 3. Section 4 summarizes the best evidence regarding the key observables and assesses the models on the basis of *these particular* constraints. Finally, in Section 4.2 I speculatively indulge in hybridizing previous models into a rather specific Galactic formation scenario that attempts to satisfy (and reconcile) many of the results from Galactic structure surveys. A latent goal of this review is to demonstrate that Galactic astronomy is a field rich in opportunity, with tractable problems to be addressed with telescopes of all apertures.

The reader is directed to the reviews by Freeman (1987) and Gilmore et al (1989; GWK hereafter) which cover many topics outside the present discussion. Information in depth can be obtained from the texts by Gilmore et al (1990) and Binney & Tremaine (1987); Mihalas & Binney (1981) is still a useful reference for fundamentals. A good historical perspective of stellar populations is given by Sandage (1986). O'Connell (1958) and Blauuw & Schmidt (1965) remain essential historical references.

1. MODELS OF FORMATION—DEFINING SOME KEY OBSERVABLES

1.1 *Formation Models for the Halo*

The modern era of Galactic structure studies may be identified with that time when the preoccupation shifted from the cosmological—the simple clarification of the order of stellar systems within the Galaxy—to the cosmogonical—the application of the properties of these systems toward ascertaining the evolutionary history of the Milky Way. This change in mindset was only technically feasible on the heels of the great theoretical and observational advances in the 1950s that made possible the joining of Galactic structure, kinematics, chemistry, and age into a unified evolutionary context. The development of a theory of stellar evolution not only made possible a means for dating the ages of stellar clusters through use of the color-magnitude diagram (Sandage & Schwarzschild 1952) but also led to an understanding of the process of nucleosynthesis (Burbidge et al 1957) and chemical enrichment. Once it was appreciated that enrichment levels were written in stellar spectra (Chamberlain & Aller 1951), the classification of individual field stars into relative age groups became possible. The relative age scale of field stars could be calibrated to that of the clusters, since it had been shown (Sandage & Walker 1955) that the peculiar, weak-lined spectra (seen as an ultraviolet excess) exhibited by some stars were shared by globular cluster stars. Decades earlier, through the work of Strömberg, Oort, Lindblad, and others, great advances had been made in the understanding of stellar kinematics and in the identification of kinematic subsystems within the Galaxy. Through Baade's (1944) insight, the association of these kinematic groups with specific structural components in galaxies was made. The final link between the structural-kinematic stellar populations and the age-metallicity groups came with the discovery by Roman (1954) that metal deficiency was correlated with high velocity.

With loose connections established between kinematic, abundance, age, and structural groupings of stars within the Galaxy, the stage was set for the development of an evolutionary picture that accounted for the existence and properties of the various stellar populations. The first major breakthrough along these lines, the landmark paper by Eggen et al (1962, ELS hereafter), remains the foundation for modern discussions of Galaxy formation. It also set the precedent for the construction of modern Galactic structure surveys. After compiling ultraviolet excesses, radial velocities, and proper motions for nearby stars, selected predominantly by large proper motion, ELS discovered smooth correlations between ultraviolet excess and (*a*) the orbital eccentricity, (*b*) the angular momentum, and (*c*) the $|W|$ velocity. Based on these correlations they constructed a formation model that incorporated new age-dating techniques into a dynamical analysis of stellar orbits. In this picture, the Galaxy formed from the rapid collapse out of the general Hubble expansion of a metal-poor, roughly spherical, primordial density fluctuation. During this collapse, condensations of gas were created and star formation turned on. The orbits of these stars today were presumed to reflect the kinematic state of the gas from which they formed, while the stellar abundances were a function of the chemical state of that gas. Thus, the earliest stars formed had the weakest metal abundances, and were born into highly radial orbits with the momentum of the initial collapse. Radial collapse was unable to continue as far as that in the Z direction because of the increase in rotational velocity and centrifugal acceleration due to angular momentum conservation. Dissipation of energy via cloud-cloud collisions enabled the gas eventually to settle into a flattened, rapidly-rotating disk. Continued star formation during the contraction allowed progressive enrichment of the interstellar medium (ISM). It is from the flattened, metal-rich disk of gas that new, circularly-orbiting stars are forming today.

Based on the apparent age of the globular clusters, ELS assumed the earliest star formation to have started 10 Gyr ago (a number that has risen with improvements in stellar evolution theory). From the $|W|$ velocities, the maximum distance from the Galactic plane, $Z_{\max}$, attained by each star was calculated. From the range in $Z_{\max}$, ELS estimated the vertical collapse to have been a factor of 25; from the ratio of apogalactica of high eccentricity to circular orbits for stars with similar angular momenta, the radial collapse was estimated at a factor of 10. Finally, the rate of the collapse was determined from the dynamical constraint that in order to form the old stars (i.e. the low metallicity stars) on highly radial (i.e. high eccentricity) orbits the radial velocity of the initially collapsing gas from which they formed must have been less than the rotational velocity (that is, $U \gg V$), or, in other words, the rate of the collapse must have been more rapid than the Galactic rotation period, established to be 200 Myr. This is approximately the timescale for freefall collapse from the estimated initial gas distances, and it was concluded that the halo of the Galaxy formed during a collapse without pressure support. As support for this idea, ELS noted: (*a*) if the gas had been hot enough to provide pressure support to slow the collapse, it would have also prevented the small-scale collapses which form stars, and (*b*) the five halo globular clusters with accurate photometry at that time all had nearly the same age.

It is the particular issue of the ELS collapse timescale that motivated first criticisms of the model and it is on this issue where much subsequent debate has centered. Isobe (1974) reanalyzed the dynamical arguments in

ELS using a similar data set and slightly different (updated) Galactic parameters, but used a model with an evolving gravitational potential. He found that although the ELS rapid contraction had difficulty accounting for the presence of some low eccentricity, low metallicity stars in the data, a slow contraction model which also included random velocities of gas clouds of a magnitude equivalent to the primordial rotational velocity, $\sim 25\ \mathrm{km\ s^{-1}}$, could not only explain these stars but also the high eccentricity stars of low metallicity which had profoundly influenced ELS to propose the short timescale. Moreover, assuming an $\sim 10^9$ year timescale for the mixing of enriched gas, Isobe pointed out that the ELS timescale would not allow sufficient time to smooth out abundance inhomogeneities and create the smooth correlations observed between kinematics and ultraviolet excess.

Saio & Yoshii (1979) and Yoshii & Saio (1979) generalized the potential calculations of ELS and Isobe to three dimensions to determine more realistic orbital parameters for their sample of stars—an especially important improvement for those with significant $|W|$ velocities (the previous work had ignored W velocities, and the adopted apogalacticon distances, perigalacticon distances, and eccentricities had been those projected in the U-V plane). They found low-metallicity, low-eccentricity stars both in their RR Lyrae sample as well as their enlarged sample of low velocity dwarfs. Thus, these stars were missing in the ELS sample not because old metal-poor stars *necessarily* have eccentric orbits as a result of their having $U \gg V$ initially, but rather because they were selected against by the proper motion bias—a point first raised by Bond (1970), and discussed frequently since (cf Mihalas & Binney 1981, their Section 7.2; Norris et al 1985). After consideration of the observed large spread in the distributions of orbital eccentricities and inclinations for old stars and those calculated in the limits of very rapid and slow collapses for a time-varying potential, Yoshii & Saio determined that the contraction period was probably $\geqslant 2$–3 Gyr. As with the Isobe model, and motivated in part by the existence of retrograde-rotating stars, the Yoshii & Saio model accounted for the wide distribution of kinematical properties for old stars in a slow collapse by including random motions of gas clouds at the initial phases of the contraction. It was the presence of a significant fraction of retrograde orbits in the halo that also prompted Larson (1969) earlier to suggest that protogalaxies were very clumpy and turbulent. Both Larson and Yoshii & Saio suggested that it was the slow dissipation rate of these turbulent clouds which supported the Galaxy against freefall collapse; this rate was determined by the balance of the kinetic energy influx from supernovae and the increase in line-cooling as supernova ejecta raised the heavy element abundance of the gas.

The idea of turbulent, slowly-contracting protogalaxies is a relatively old one (cf von Weizscker 1951, Oort 1958); however, it underwent a resurgence of popularity starting in the late 1970s due to developments in both extragalactic and Galactic studies. On the extragalactic side came the recognition of the ubiquity of galaxy interactions and mergers and the possibility that the evolution of some galaxies may have been quite tumultuous, perhaps the result of a hierarchical sequence of mergers among subsystems (Toomre 1977, Vorontsov-Velyaminov 1977, Tinsley & Larson 1979). The idea of a quite inhomogeneous Galactic beginning received additional support from the highly influential work on the Galactic globular cluster system by Searle (1977) and Searle & Zinn (1978, SZ hereafter). They noted that: 1. in almost all clusters, there is no detectable metallicity spread in the constituent stars, 2. there is no radial abundance gradient in the outer halo ($R > 8$ kpc) globulars, and 3. for the inner halo clusters, there is a direct correlation of abundance to horizontal branch (HB) morphology, while the outer halo clusters show a spread in HB morphology at any given metallicity. That is, outer halo globulars exhibit a significant "second parameter" effect in their HBs which is not seen in the inner halo. The lack of an abundance gradient in the outer halo globulars is perfectly consistent with the ELS model of rapid collapse: If globulars formed from material in freefall, their kinematics are independent of their abundance, and, even if there was progressive enrichment, subsequent dynamical mixing would have removed any spatial gradient. The lack of a halo abundance gradient (see Section 3.4.1) is *inconsistent* with a slow pressure-supported collapse whence mean abundance slowly increases with the continuing Galactic contraction and rotational spin-up. SZ pointed out, however, that while the ELS model may be consistent with point 2, it may be overly specific in requiring a rapid collapse: "the minimum requirement seems to be that these clusters were formed in such a way that, when they came into dynamical equilibrium with the galactic system, their kinematics were uncorrelated with their abundances." Moreover, Searle pointed out that fact 1 is hard to account for if clusters formed during a rapid collapse, since freefalling material is unlikely to be chemically mixed at the level of homogeneity observed within each cluster; rather the clusters must have formed out of larger structures or "fragments" each of which had evolved independently, became enriched, and mixed internally. Later, these fragments could be destroyed by supernovae or tidal effects. *If* age is the second parameter of HB morphology (see Section 3.2.2), the cluster distribution supports the idea of a slower, more chaotic collapse for the outer halo and a more rapid formation in the inner halo. Together, facts 1–3 suggested to SZ a picture in which the halo clusters and stars formed in transient gaseous fragments, similar to gas-rich, irregular galaxies, which continued to fall into dynamical equilibrium with the Milky Way well after the main collapse had formed the inner regions of the Galaxy. The strong second-parameter effect in the outer halo is commonly viewed as evidence that the halo formed over several gigayears, and not in the rapid collapse suggested by ELS.

With the evidence of a significant number of retrograde orbiting stars, the existence of low-metallicity stars with low eccentricity, and the number of arguments in favor of a more chaotic, slow formation of the halo, is the ELS model to be abandoned? Sandage (1990a) has argued strongly that 1. the ELS scenario as originally postulated is a "first order," limiting model of formation in a constant density medium without "kinematic noise," and that nowhere in the original paper was codified the popular conception that the model *requires* a monolithic, homogeneous collapse, and 2. the SZ model represents the next level of complexity—it is "ELS plus noise." Sandage notes that with the added complexity of density noise, consistency with the longer formation timescale is obtained through a hierarchy of collapse times related as $t \sim (G\rho)^{1/2}$. Kinematic noise would account for the existence of retrograde orbiting stars. The existence of low-metallicity stars with low eccentricity is a result of noise in the age-metallicity relation (AMR). One of Sandage's main criticisms of ELS was that it specified a "rapid" collapse timescale (<200 Myr) based on the rotation period of the *present Galaxy at the solar circle*. (As was pointed out earlier by Isobe (1974), a longer timescale would have been obtained if instead conditions in the more extended, primordial state had been considered.) But more significant is Sandage's suggestion that, in view of the properties of IPII and the fact that most ELS stars have $Z_{max} < 5$ kpc, the ELS model for the formation of the halo pertains instead to the formation of IPII.

An issue that has been a legacy of confusion is that regarding halo metallicity gradients and the original ELS picture. If star formation in freefall cannot generate a metallicity gradient, and if only in a contraction slow compared to the enrichment timescale can a gradient occur, then how is it that the lack of a metallicity gradient is commonly used to argue *against* the ELS model? The birth of this notion lies perhaps with the paradoxical and apparently conflicting evidence that 1. Sandage and collaborators (Sandage 1969, Sandage & Fouts 1987) continued to find smooth correlations between kinematics and abundance which were argued to support the ELS picture, whereas 2. SZ, in their reanalysis of the Sandage (1969) data, concluded that there was no evidence that abundance was correlated to kinematics for stars more metal poor than [Fe/H] $= -1$, thereby corroborating the globular cluster evidence used to support the chaotic, fragment model. The resolution of this longstanding debate lies first with the definition of when and where the ELS "freefall" era ended and when the slower dissipative formation of the disk occurred, and second with the understanding of which regime the ELS stars actually explore. It is important to note that in the discussion of their Figure 5, which apparently showed a correlation between mean Z-height reached and ultraviolet excess, ELS stressed only that "the oldest objects were formed at almost any height above the galactic plane, whereas the youngest were formed very near the plane.... It appears, therefore, that a collapse of the galaxy into a disk, either after or during the formation of the oldest stars, is required...." At no point did ELS specify that abundance is correlated with kinematics *within the halo*; rather, they discuss two distinct generations of stars: 1. a first generation formed during the Galactic collapse which now have eccentric orbits, and 2. a generation of stars formed after the collapse which have the nearly circular orbits in which their parent gas clouds had settled. The variation in ultraviolet excess between the populations was attributed to a time lapse between the two generations long enough to permit enrichment by supernovae from the first stars formed. Only in the broadest sense is this two-generation scenario of ELS interpretable as having a correlation of kinematics to abundance. It is the semantics of this description that seems to have become convoluted with time, and it is the nature of the transition from halo to disk—in each of the spatial, abundance, and kinematic domains—which has become central to ongoing debate. To wit, considerable attention has now been placed on explaining IPII, which has become a critical focus for discriminating between evolutionary models (Section 1.2), and which is now recognized to be the dominant population in the ELS sample (Section 2.1.1).

1.2 *Formation Models for Intermediate Population II*

Numerous models for the formation of IPII have been put forward (see GWK, Gilmore et al 1990) since the confirmation of its existence a decade ago by Gilmore & Reid (1983). These models are summarized in Table 1 along with characteristics of the age, abundance, and kinematic distributions expected from each. Models are also distinguished by their prediction regarding the kinematic and chemical discreteness of IPII from both the halo and thin disk. Essentially, the models fall into either "top down" scenarios, where the formation of IPII precedes the formation of the thin disk, or "bottom up" scenarios, where IPII is the result of some action on or by the thin disk.

1.2.1 PRE-THIN DISK MODELS In the pre-thin disk models, the formation of IPII is a transitional phase during the general contraction of the Galaxy.

Table 1 Models of Intermediate Population II Formation

Model	Thin disk disjoint?	Halo disjoint?	Key age features	Key abundance features	Key kinematic features
Pre-thin disk ("top down") models					
1. First phases of partial pressure support as gas begins dissipational collapse (Sandage 1990a)	No	No	No age gap with halo	Gradient	Gradient
2. Rapid ELS collapse, gap in star formation, then pressure-supported collapse (Larson 1976; Gilmore 1984)	No	Yes	Age gap with halo	Gradient	Gradient
3. Rapid increase in dissipation due to line radiation cooling (Wyse & Gilmore 1988; Burkert et al 1992)	No	Yes	Small range of age	[Fe/H] > −1, little/no gradient	Gradient
4. Formation disconnected from halo, "disk first" (Jones & Wyse 1983, Norris & Ryan 1991)		Yes	Can overlap with halo		
Post-thin disk ("bottom up") models					
5. Secular kinematic diffusion of thin disk stars (Norris 1987)	No	Yes	Wide range of ages. Gradient, overlaps thin disk.	Gradient, [Fe/H] ≤ old disk	Gradient
6. Violent thin disk heating by satellite accretion (Carney et al 1989; Hernquist & Quinn 1989, Quinn et al 1992)	Yes	Yes	Older than oldest thin disk star	Expansion of disk gradient at event	Modest asymmetric drift, radial σ_z gradient
7. Accretion of thick disk material directly, e.g. debris of accreted satellite	Yes	?	Lots of possibilities	Probably no gradient	?
8. Halo response to disk potential (van der Kruit & Searle 1981a,b; Gilmore & Reid 1983)	Yes	No	As old as halo	Halo metallicity properties	Halo (large) asymmetric drift

The nature and relationship of IPII to other Galactic components are the product of the histories of star formation and dissipation during the contraction. The former drives the enrichment timescale and is reflected in abundance distributions; the latter is reflected in kinematical distributions. Incipient with the onset of dissipation is a switch from pressure to rotational support. In general, the pre-thin disk models view the IPII as a dissipative, rotationally-supported structure, and the halo as non-dissipative and supported by the kinetic pressure provided by large, anisotropic velocity dispersions. The thin disk represents the final stage in the dissipative settling of disk gas. The main distinctions between Models 1–4 in Table 1 stem from the history of star formation preceding and during the transition to the flattened, dissipative structure. In the first model, discussed by Sandage (1990a), star formation is continuous throughout formation of the halo—which, as in ELS, is proposed to occur during freefall—and IPII—which is proposed as that structure resulting from the "first phases of partial pressure support." In this scenario, the chemical and kinematical properties of the halo and IPII are rather smoothly joined, and there would be no age gap between the first IPII stars formed and the youngest halo stars.

On the other hand, Larson (1976), and later Gilmore (1984), stressed the need for a large reduction in the star formation rate (SFR) after freefall formation of the halo in order to permit gas to settle into a disk before resumption of star formation in the disk. Larson explored several means of suppressing star formation between the formation of the halo and disk components, including a dependence of the SFR on the (decreasing) velocity dispersion, tidal inhibition from the spheroid, and depletion of dense clouds (which formed the halo population) in a two-phase protogalactic gas structure. Gilmore suggested disruptive mechanisms such as tidal shocks, supernovae, and destructive cloud collisions. But intense heating of the substantial fraction of remaining gas following the initial burst of (halo) star formation alone might be sufficient to suppress star formation (Marsakov & Suchkov 1977), with energy, momentum, and metal-enriched material injected from the star-forming clouds into the pre-disk ISM in the form of strong galactic winds (Silk 1985, Berman & Suchkov 1991); the delay while the metal-enriched gas recontracts and cools out of this hot, expanded phase and eventually forms the disk may last several gigayears (Berman & Suchkov 1991, Burkert et al 1992, Katz 1992). In these "suppressed star formation" pictures (Models 2 & 3), the stars of the halo and IPII should have discrete chemical and kinematical distributions, and be separated by an age gap.

The subsequent evolution of the intermediate disk phase is dictated by the pace of dissipation, cooling, and star formation. In the Larson (1976) picture (Model 2), events proceed at a relatively gradual pace which allows the development of vertical age, kinematic, and abundance gradients. In contrast, Wyse & Gilmore (1988) have argued for a more rapid IPII formation phase which corresponds to a dramatic increase in the dissipation rate when the metallicity of the 10^6 K gas reaches $[Fe/H] \approx -1$ and the dominant cooling mechanism switches from free-free radiation to more efficient line radiation. The increased cooling rate also leads to increased star formation. A similar scenario leads to a brief (400 Myr long) thick disk formation phase in the disk formation model of Burkert et al (1992). The result (Model 3) is an extended, IPII disk component with a very small age range (200–300 Myr), which, with little chance for the recycling of enriched material, has little or no metallicity gradient. The evolution to the thin disk phase is dictated by the SFR as the gas further dissipates. Burkert et al (1992) describe a rapid decline in the SFR—by a factor of 10 in the first 5 Gyr of gravitational settling—and a more gradual decline thereafter; nonetheless, this smooth, "dribbling" transition to the thin disk implies continuous age, metallicity, and kinematic gradients between the thin disk and IPII. The idea of more discrete star formation bursts for each IPII and the thin disk has also been put forward (Marsakov & Suchkov 1976, 1977, Gilmore 1984, Gilmore & Wyse 1986, Marsakov et al 1990), perhaps with a renewed phase of star formation suppression in between.

Distinct from this model with a break in star formation, is a model with *disconnected* halo and IPII star formation (Model 4). A gaseous disk might be the *first* major Galactic structure to form (Jones & Wyse 1983), but with some gas left behind as, for example, SZ "fragments." Star formation then proceeds independently (and simultaneously) in the disk and fragments; the latter may be accreted or destroyed at later times and be a source of halo field stars and clusters (SZ, Norris & Ryan 1991). Afterwards, disk formation might proceed along one of the scenarios already outlined, e.g. Model 2 or 3.

As IPII continues its dissipative collapse, there is contractional spin-up similar to that postulated in the ELS scenario; thus Models 1–3 each predict IPII kinematic gradients with Z. In the process of self-regulated disk settling described by Burkert et al (1992; see also Silk 1985), where heating of the intercloud medium by supernovae is balanced by dissipation through cloud-cloud collisions, a vertical velocity dispersion gradient arises naturally because the dispersion is related to the sound speed of the intercloud medium which declines as it gradually cools. If the dissipational collapse timescale is long enough to permit enrichment of the ISM, as in Models 1 and 2, and some versions of model 4, then the increase in the mean metallicity of new stars will give rise to a vertical IPII metallicity gradient (Sandage 1990a, Larson 1976, Gilmore 1984, Norris & Ryan 1991), which may smoothly join to that of the thin disk (Norris & Ryan 1991). Note that the models of Larson (1976) and Jones & Wyse (1983) which build the disk from the bulge outward (see also Burkert et al 1992) also predict very strong radial metallicity gradients in the disk components.

1.2.2 POST-THIN DISK MODELS Stars in the Galactic disk may be subject to a variety of stochastic heating mechanisms that lead to an increase in their velocity dispersion and kinematic diffusion from the Galactic plane (see Fuchs & Wielen 1987; Wielen et al 1992). It is natural to suggest that processes which kinematically heat thin disk stars might also be responsible for producing the IPII as a tail in the distribution of secular diffusion (Norris 1987; Model 5). Under such circumstances IPII would be discrete from the halo but smoothly joined to the thin disk. Gradients in age, kinematics, and metallicity would be expected, since older, presumably more metal-poor disk stars would have experienced more stochastic events than their younger, metal-rich counterparts. Viable processes of stellar diffusion require encounters with large irregularities in the disk gravitational field, and three main mechanisms have been proposed:

1. Original investigations into the origin of the age-velocity dispersion relation (AVR; Spitzer & Schwarzschild 1951, 1953) focused on encounters with molecular clouds wherein it was concluded that complexes of $\sim 10^6\ M_\odot$ would be required to account for observed distributions of Population I stars. Even though such giant molecular cloud complexes are now known to exist, it was clear even then that this process alone would still not account for the velocity dispersions of IPII stars (i.e. "general high velocity stars"). Later investigations (Lacey 1984, Villumsen 1985, Binney & Lacey 1988) have indicated that the present density of such large GMCs is too small to have created the velocity dispersions of even the hottest observed thin disk stars.
2. An AVR can be created by the action of transient disk instabilities, such as spiral arms or wavelets (Barbanis & Woltjer 1967, Carlberg & Sellwood 1985); however, this action is predominantly coupled only to the planar motions and spiral arm heating is generally ineffective for vertical motions (Carlberg 1987). Recent studies (Carlberg 1987, Binney & Lacey 1988, Jenkins & Binney 1990) have therefore concentrated on the combined action of spiral waves and GMCs to increase vertical velocity dispersions and disk scale heights, with the former acting as the main source of heating, and with the GMCs deflecting the heated stellar orbits up out of the Galactic plane.
3. Binney & Lacey (1988) suggest that to obtain $\sigma_W \geqslant 40$ km s^{-1} short-lived disk perturbations are needed, and they propose fast moving,

massive objects on orbits inclined to the disk—dwarf galaxies or supermassive halo black holes—as the likely agents. Ipser & Semenzato (1985) and Lacey & Ostriker (1985) find that massive, $10^6\ M_\odot$ black holes can explain not only the observed form of the AVR for thin disk stars but also the existence of the mysterious high velocity A stars and the (presumably young) high velocity F stars with solar metallicity (Rodgers et al 1981; Stetson 1981a,b; Lance 1988a). If they are the only dark matter constituents, something like 10^5–10^6 of these exotic objects is implied; yet none has been detected so far. Even if they did exist, disk heating by $10^6\ M_\odot$ black holes apparently seems incapable of forming an IPII with as much as 10% of the total disk surface mass density (Lacey & Ostriker 1985), the fraction implied by recent star count analyses (Section 3.1).

In principle, since each diffusive mechanism makes a specific prediction regarding the form of the AVR, it should be possible to test them on the basis of observational data. Unfortunately, studies of A–F dwarfs in the solar neighborhood (Mayor 1974; Wielen 1974, 1977; Carlberg et al 1985; Knude et al 1987; Strömgren 1987; Meusinger et al 1991; Wielen et al 1992; Freeman 1993) remain surprisingly controversial and, taken together, rather inconclusive on the form (continuously rising versus flat or "saturated") and size of the AVR, especially for older (> 6 Gyr) stars. However, there is general agreement that dispersions of *at most* $\sigma_W \approx 15$–25 km s^{-1}, and not the $\sigma_W \approx 45$ km s^{-1} observed for IPII, can be attained in 10–15 Gyr.

Alternatively, the thin disk may have experienced one or more events of violent dynamical heating, perhaps through the accretion of Galactic satellites (Carney et al 1989). On the basis of simple dynamical friction arguments, Ostriker & Tremaine (1975) showed that the orbits of satellites in dark matter halos should decay and may lead to accretion by parent galaxies. Inserting Galactic parameters into the model yields a total mass accumulated in a Hubble time of $2 \times 10^{10}\ h_o\ M_\odot$, or the equivalent of one LMC mass (Hernquist 1991, Hernquist & Quinn 1993). It is noteworthy that the model of dissipational galaxy formation within dark matter halos by Katz (1992) not only produces satellite galaxies, but early disk mergers of these satellites which result in thickened disks. But Tóth and Ostriker (1992) have argued that the present thickness of the dynamically "cold" *thin* disk near the sun provides the severe constraint that less than 4% of the mass within $r_\odot$ could have derived from the accretion of satellites within the last 5 Gyr. There are several ways to satisfy both theoretical calculations: 1. The satellites may be destroyed before they reach the disk, in which case their remnants may be evident in (as?) the Galactic halo. 2.

Quinn & Goodman (1986), Hernquist & Quinn (1989), and Quinn et al (1992) have shown that accreted satellites sink towards the plane of the Galaxy before they sink radially inward. Thus, significant dynamical heating may occur at large r where thin disk velocity dispersions might be larger than those found locally. 3. Finally, and of most interest here, the IPII may be the dynamically heated disk expected in the Tóth and Ostriker scenario (Model 6).

The most thorough examination of the problem of accretion-induced heating of galactic disks has been the N-body simulations of Quinn et al (1992). Merging of satellites on inclined, prograde orbits takes several rotation periods and an equilibrium status is reached in about 3 Gyr. Quinn et al predict the following properties of post-merger disks: 1. An overall increase in the scaleheight and vertical velocity dispersion of disk stars by a mean factor of about two at radii equivalent to $r_{\odot}$. 2. Significant outward gradients in both the scaleheight and vertical velocity dispersion which result in a flaring of the disk. 3. For inclined satellite orbits, warps are formed in the outer disk, and these may persist for 3–5 Gyr. 4. Only a modest increase in the asymmetric drift from that of the original disk.

Because thin disks are "destroyed" in the merging process, any thin disk we see today must have formed subsequently to any merger event. Therefore the thickened disk stars must be older than the oldest stars in the thin disk. Quinn et al have also determined that existing vertical kinematic and abundance gradients in the original thin disk will be preserved, or slightly enhanced, in the post merger disk. However, since the age of the Galactic thin disk (Section 3.2.1) appears to place any major merger event at times more than 10 Gyr ago, it may be that any previously existing metallicity gradient was small. It is worth reiterating that the fragility of thin disks suggests a relatively small mass infall rate (at least in the form of large, dense clumps) over the age of the present thin disk, a point with important implications for chemical evolution models.

A related model for the origin of IPII, but one which has had less theoretical exploration, is that it represents the accumulation of debris from accreted satellites that were destroyed *before* their orbits sank into the Galactic plane (Model 7; GWK). Statler (1988) has shown that in some circumstances, the remains from tidally stripped satellite galaxies might populate inclined, thin tube orbits which would give rise to a "boxy" distribution. However, this apparently requires rather special initial conditions which either put the satellite on a low eccentricity orbit at $R < 30$ kpc and/or require a dark matter halo that truncates at $R = 30$ kpc.

Model 8 was proposed soon after the discovery of "thick disks" in edgeon galaxies (Tsikoudi 1979, 1980; Burstein 1979; van der Kruit & Searle 1981a,b) and its delineation in our own Galaxy (Gilmore & Reid 1983): IPII is simply a flattening response of halo stars to the gravitational potential of the thin disk (Model 8; Freeman 1980, van der Kruit & Searle 1981a,b, Gilmore & Reid 1983). *N*-body simulations by Barnes & White (1984) explored the case of disks deforming *bulge* components but were not able to produce thick disks. Binney & May (1986) discussed other dynamical methods for redistributing halo stars into less inclined orbits. More recently, with the conclusion that there is no substantial amount of missing mass in the Galactic disk (Kuijken & Gilmore 1989), Gilmore et al (1990, Section 13.9) have suggested that the surface mass density of the disk is too small to distort the halo by gravitational means. In Model 8 the IPII is simply a part of the halo so it should exhibit a very large asymmetric drift velocity, $\langle[\mathrm{Fe/H}]\rangle \approx -1.6$, and an age commensurate with halo stars.

Finally, it is worth noting that thick disks are not observed in all disk galaxies (van der Kruit & Searle 1981a)—circumstantial evidence that would tend to support the occurrence of random formation events, such as satellite accretion (Section 3.5) or global bursts of star formation (cf Section 3.2.1), rather than a requisite formation phase in all disk galaxies. Note too that any post–thin disk, heating scenario (Models 5 or 6) must also account for the presence of the disk globular clusters at large Z (cf Armandroff 1989), if these are members of the IPII (see Section 2.1.3). In the end, the actual process of Galaxy evolution is likely to be more complicated than any one of the naively separated models presented here, and some combination of these processes has likely occurred, as for example, in the scenario of Norris & Ryan (1991), which incorporates elements of both models 4 and 5, as well as secondary gas infall.

2. THE ELEMENTS OF GALACTIC STRUCTURE SURVEYS: CAVEATS AND CHALLENGES

2.1 *Types of Galactic Structure Surveys*

Before proceeding with observational tests of formation models, it is useful to review the structure of Galactic structure surveys themselves. The goal of this section is to project both an appreciation of the many survey efforts as well as to provide benchmarks with which to judge the reliability of the various elements within each. Three main types of surveys have been applied to the study of Galactic structure: 1. *selected surveys* identify members of the various Galactic populations in the solar neighborhood on the basis of assumed kinematic or chemical properties, 2. *tracer surveys* use star clusters or intrinsically luminous stars as tracers of Galactic populations at large distances from the sun, and 3. the so-called *in situ surveys* also probe to distances beyond the solar neighborhood but, in distinction to the tracer surveys, by studying complete samples of stars, the bulk of which are dwarfs.

2.1.1 SELECTED SURVEYS FROM THE SOLAR NEIGHBORHOOD A large amount of the progress made in the past three decades of Galactic studies can be attributed to the success of the selected surveys, of which ELS is the prototype, and in particular, the proper motion and/or metallicity-selected surveys of Norris et al (1985), Sandage & Fouts (1987), Carney et al (1990b), Ryan & Norris (1991), and Schuster et al (1993). The motivation of these programs is the efficient identification of nearby stars with extreme properties—high velocity and low metallicity—thought to be associated with older populations of the Galaxy. Selected surveys like ELS face three fundamental complications:

1. There may exist whole classes of stars which, if unseen and unaccounted for, may belie very important pieces of the evolutionary puzzle. An example are the metal-poor stars with disk kinematics discussed above (Section 1.1); these were missed by the ELS proper motion selection but found via other means by Yoshii & Saio (1979) and Norris et al (1985), although less extreme ([Fe/H] $\geqslant -1$) examples were known decades earlier (Wallerstein 1962). Sommer-Larsen & Zhen (1990) have estimated the amount of phase space accessible in their metallicity-selected survey of halo stars; they were able to reconstruct the halo at $8 \leqslant R \leqslant 20$ kpc with 90% completeness, but faced significant incompleteness for $R < 8$ kpc since most of these stars never reach $r_{\odot}$.
2. With a kinematically-biased survey, measurements of kinematical quantities will be overestimated due to the selection against stars with near-solar kinematics (Vyssotsky & Williams 1944, Dyer 1954, Bond 1970). Bahcall & Casertano (1986) and Ryan & Norris (1993) have demonstrated how errors in measured V and σ_U as large as 25% are possible.
3. Selected surveys are localized to a few hundred parsecs of the Sun—the region of maximal spatial overlap of the different populations that the surveys aim to study. The additional overlap in the kinematic and abundance domains leads to severe problems in disentangling the population mix. As a noteworthy case in point, it is now established (Sandage & Fouts 1987, Sandage 1990a, Norris & Ryan 1991) that the ELS sample itself, in particular the stars which appear to show the correlation of abundance to kinematics, is not dominated by the halo,

but by IPII.[4] In order to cope with degeneracies in parameter space, surveys of stellar populations generally follow one of two tacks: (*a*) They attempt to isolate "pure population samples" by assuming dominance of a given stellar population within a certain range of a variable (for example *V*, *W*, [Fe/H], or, as in the tracer and in situ surveys, *Z*). An implicit assumption is that any parameter measured from such samples is independent of the isolating parameter, and the degree of success is heavily dependent on the "non-overlappingness" of the isolating parameter between populations. (*b*) They model the mixing of the populations and their (overlapping) parameters.

2.1.2 MODELING OF SELECTED SURVEYS Computer-generated models of selected surveys allow not only a more self-consistent approach to the separation of Galactic subsystems, but can also be used to assess the effects of selection biases and error propagation. Modeling of stellar systems can be traced back to the early part of this century when it was applied to the interpretation of the newly discovered "star streams" by Kapteyn, Eddington, Schwarzschild, Strömberg, Oort, and others, and perhaps reached the height of complexity in Lindblad's (1927) model of continuous distributions through an infinite number of discrete components (see Nemec & Nemec 1991 for a review of the early stellar population models). Many of the earliest computer models were applied to the interpretation of *magnitude-limited* data—for example the starcount models of Bahcall & Soneira (1980, 1984), Gilmore (1984), Robin & Crézé (1986), and Yoshii et al (1987)—an application still receiving attention (Reid & Majewski 1993). Recent incarnations of the Bahcall & Soneira model (Ratnatunga et al 1989, Casertano et al 1990) also include kinematics (see also Chiu 1980), while the Robin & Crézé (1986) model includes both kinematical and evolutionary dimensions. Early computer models specifically aimed at understanding *proper motion–biased* surveys include Reid (1984), Richstone & Graham (1981), Bahcall & Casertano (1986), and Dawson (1986). Each used simulations of stellar kinematics to estimate the local density of halo stars from the number of high proper motion stars in the catalogues of Giclas et al (1968, LPMS hereafter), Eggen (1979, 1983), and/or Luyten

[4] In retrospect, this discovery that a large fraction of the stars in either proper motion or metallicity-selected surveys are from the *IPII* should not have come as a surprise since 1. the high velocity stars had initially been recognized as a *disk* population, distinct from the "subdwarfs" of Population II (see the discussion by Roman 1965), and 2. it had already been shown that there existed a large population of stars with disk-like kinematics which would be found with a metal-poor selection (Wallerstein 1962) as well as a population of stars which were only slightly metal poor which would be found with a high velocity selection (Keenan & Keller 1953).

(1976). This may only be determined after parameterizing the kinematics of halo *and* disk populations and modeling catalogue proper motion, magnitude, and galactic coordinate biases. The local halo fraction then follows from either tack above: either (*a*) by adopting a suitable transverse velocity (V_t) limit to isolate halo stars (Richstone & Graham, Bahcall & Casertano, after Schmidt 1975 and Eggen 1983); or (*b*) by calculation of the relative "discovery fractions" of the various components (Reid and Dawson). Unfortunately, a great disparity of results is obtained; the inferred halo density is very sensitive to both the kinematic model and the adopted V_t. Bahcall & Casertano have stressed that V_t limits even slightly permissive of high velocity disk stars can cause gross overestimates of the halo density.

Ever more elaborate and sophisticated models are being applied to the problem of population decomposition (Norris & Ryan 1989b, Casertano et al 1990, Nemec & Nemec 1991, Ratnatunga & Yoss 1991, Norris & Ryan 1991), with a prime motivation being the ascertainment of the minimum number of discrete components (Section 1.2) needed to interpret the data. These models have been applied most often to stellar samples from proper motion catalogues (the LPMS; and Luyten 1979 et seq, NLTT hereafter). While this culling is predominantly through specific proper motion, color, magnitude, and coordinate criteria, other, more complicated biases may have also been imposed (some unintentionally)—e.g. selection against apparent white dwarfs, orientation of the proper motion vector, magnitude dependent-color cuts—while other selection biases are prone to nonuniform application because they are either nonquantitative in nature (e.g. selection by LPMS color class) or based on quantities measured with less accuracy (e.g. photographic magnitudes). Casertano et al (1990) stress the difficulty in accounting for these various selection biases, the complexity of which has prompted at least one new observational program designed to mitigate their effects (cf Carney 1993). The work of Norris & Ryan (1991) highlights the difficulties still confronted by even the most advanced models: They find that the distributions of kinematics as a function of abundance in the Carney et al data are fit equally well by both three-component ("discrete thick disk") and two-component ("extended disk") models (though for other reasons they find the extended disk model to be "superior"). This is in contrast to the conclusion of Ratnatunga & Yoss (1991) whose modeling of the Yoss et al (1987) data led them to advocate the discrete thick disk model. Thus, while it appears that the halo is kinematically and chemically discrete from the IPII (Norris 1986; Carney et al 1989, 1990b; Norris & Ryan 1989b; Majewski 1992a), even sophisticated and detailed modeling has not resolved the issue of IPII/thin disk discreteness. Note that in general the models assume symmetric, Gaussian distributions of properties for each component, with no interrelation between variables (so-called univariate models; the Norris & Ryan 1991 extended disk being a notable exception), whereas recent evidence suggests asymmetric, non-Gaussian distributions of kinematics (Norris & Ryan 1989b, Schuster 1990) and metallicity (Carney 1993) in the halo, and possible IPII gradients in kinematics (Section 3.3.1) and metallicity (Section 3.4.2).

2.1.3 TRACER SURVEYS One way to overcome the confusion of mixed populations is to leave the solar neighborhood and shed populations of lower scaleheight. Thus, one may use halo measurements at large Z (>6 kpc, see Section 3.1) to infer IPII characteristics at moderate Z, and, combining the two, of the thin disk at low Z . This method requires both prior knowledge of the various density distributions and faith in the extrapolations particularly since the tracers used—globular clusters or evolved stars—represent only a small fraction of the total stellar mass density and are highly sensitive to age, chemical composition, and star formation history.

A number of giant star surveys have succeeded in probing stellar populations away from the thin disk (Bond 1980; Hartkopf & Yoss 1982; Norris et al 1985; Ratnatunga & Freeman 1985, 1989; Carney & Latham 1986; Friel 1987; Yoss et al 1987; Norris & Green 1989; Morrison et al 1980; Morrison 1993). While samples of giant stars can be affected by the various problems mentioned above, two other commonly used tracer species—HB stars and globular clusters—face addtional complications which make them even less obvious to interpret.

Globular clusters Globular clusters have been used to define the kinematics (Section 3.3.2), the metallicity distribution (Zinn 1985, Laird et al 1988b), and the age distribution (Section 3.2.2) of the halo, as well as to determine the distribution of mass within the Galaxy (Hartwick & Sargent 1978, Frenk & White 1980, Olszewski et al 1986, Carney et al 1990, Zaritsky et al 1989). With the clearer recognition of the earlier suspicion (Becker 1950, Morgan 1956, Baade 1958, Kinman 1959) that the globular cluster system divides into a halo and disk population (Zinn 1985, Hesser et al 1986, Armandroff & Zinn 1988[5]), roughly at [Fe/H] ≈ -0.8 (Zinn 1985, Armandroff & Zinn 1988), the metal-rich globular cluster system has also been used as an IPII tracer (e.g. Armandroff 1989, 1993; Layden 1993). However, this division is not definitive; several intermediate metallicity globulars with disk kinematics have now been identified (cf Cud-

[5] See also the discussion by Marsakov & Suchkov (1976) of earlier work (in Russian) by Mironov & Samus.

worth & Hanson 1993)—M28 ([Fe/H] < -1.2), M107 ([Fe/H] $= -1.0$), and possibly M4 ([Fe/H] $= -1.3$). Moreover, the number of clusters is relatively small and it is not obvious how the present globular cluster system relates to the larger mass of field stars. One known difference between them is the [m/H] distribution (Laird et al 1988b). Clusters are also destroyed by evaporation, dynamical friction, disk shocking, bulge shocking, and possibly even bar shocking (cf the review by Spitzer 1987; also Fall & Rees 1977, Chernoff & Shapiro 1987, Aguilar et al 1988, Long et al 1992). These processes act selectively and the range of cluster properties narrows with time (Fall & Rees 1977). Thus, the present globulars are dubious tracers of either the original cluster population, those cluster stars which have been contributed to the field, or field stars which may have been generated in processes unrelated to globular clusters altogether (Caputo & Castellani 1984).

Field horizontal branch stars RR Lyrae stars (Saha 1985, Hawley et al 1986, Strugnell et al 1986, Suntzeff et al 1991, Kinman 1992, and references therein) and blue HB stars (BHBs; Pier 1984, Sommer-Larsen & Christensen 1989, Preston et al 1991) have played an important role in understanding the halo because they are visible to great distances and readily identifiable in Schmidt telescope surveys by their blue color, variability (RR Lyraes), or deep Balmer absorption in objective prism spectra (BHBs). Earlier, Preston (1959) discovered that metal-rich RR Lyraes are concentrated toward the Galactic plane; now these stars are being applied as tracers of IPII (Rodgers 1991, Suntzeff et al 1991, Layden 1993). There are at least two important selection effects in HB tracer surveys: 1. lower metallicity ([Fe/H] < -1.6, $\Delta s \geqslant 8$) RR Lyraes of type ab are harder to find because they have longer periods and exhibit smaller magnitude variations (Butler et al 1979), and 2. the morphology of the HB, i.e. the relative numbers of BHBs, RR Lyrae, or red HB (RHB) stars, depends on the chemical composition of the parent population as well as age, and any other possible "second parameter" variables. Thus, to trace stellar populations one ought to use the *entire* horizontal branch—i.e. BHB + RR Lyrae + RHB. Unfortunately, RHBs, found most often in metal-rich populations, are not as easy to find and identify unambiguously. Previous surveys for IPII RHBs have led to widely discrepant number densities (Section 3.2.3). Unless the RHB number density can be inferred, it is difficult to assess chemical composition and second-parameter effects on the other HB species. Thus, RR Lyrae and BHB stars are most reliable as tracers in the absence of age and metallicity gradients. It is fortuitous that the outer halo appears to satisfy at least the latter requirement (Section 3.4.1). On the other hand, the BHB surveys must also contend with the problem of confusion with blue stragglers (Norris & Hawkins 1991) and even main sequence A stars (Lance 1988b, Green & Morrison 1993).

2.1.4 IN SITU SURVEYS OF DWARF STARS An alternative way to study stellar populations at large Z while avoiding the selection effects of tracer surveys is to study the bulk of the stellar populations—the dwarf stars—*directly*. The necessary magnitude limits are the most daunting challenge for these surveys; e.g. even at the Galactic poles a magnitude limit of $V \approx 20$ is required to reach pure halo samples of G dwarfs (Section 3.1), and their density is little more than 100 deg^{-2} at that depth (Reid & Majewski 1993). Only a handful of complete surveys of dwarf stars have probed to $V \geqslant 20$: counts and colors by Kron (1980, $B \leqslant 24$), Jarvis & Tyson (1981, $B \leqslant 24$), Becker et al (1982, $V \leqslant 21$), Reid & Majewski (1993, $V \leqslant 22$) and proper motions as well by Chiu (1980, $V \leqslant 21$), Koo et al (1986, $B \leqslant 22.5$), Majewski (1992a, $B \leqslant 22.5$), and Guo et al (1993, $B \leqslant 22.5$). Such deep surveys must contend with the problem of extragalactic contamination. The ability to separate stars from galaxies is especially critical, since the latter outnumber stars by an order of magnitude at $V \approx 22$, and continue to increase in density more rapidly than stars; thus, even a small galaxy contamination can heavily influence a starcount survey. High resolution imaging (Richer & Fahlman 1992) can minimize galaxy contamination, but has not alleviated the problem of QSO contamination. Both Richer & Fahlman and Richstone et al (1992) have probed to $V \approx 24$ in order to determine the contribution of faint stars to the total mass of Galactic baryonic dark matter, but the former suspect half of their stellar objects to be QSOs. This is consistent with projections from brighter star and QSO counts. Reid & Majewski (1993) have pointed out that even at $V \approx 21$ QSO contamination can significantly boost the apparent number of blue halo stars.

2.2 *Abundances and Radial Velocities*

2.2.1 PHOTOMETRIC ABUNDANCES Spectroscopically-determined abundances are always a preferable, but not always a practical, alternative to photometric estimation of stellar abundances. A mainstay of Galactic astronomy has been the use of the ultraviolet excess, $\delta_{0.6}$ (U-B) (Sandage 1969), as a measure of the degree of line blanketing for F and G stars with $0.3 \leqslant B-V \leqslant 0.8$, and more recently this technique has been pushed to $B-V = 1.2$ (Sandage & Kowal 1986, Majewski 1992a, but see Ryan 1992). Translation to [Fe/H] has most often relied on the calibration by Carney (1979). One shortcoming is the loss of sensitivity for [Fe/H] $\lesssim -2$. In principle, with 1% photometry, $\delta_{0.6}$ metallicities accurate to [Fe/H] $\approx \pm 0.2$ are expected for more metal-rich stars; in practice, however, the accuracy appears to be no better than twice this (Norris & Ryan 1989b, Schuster & Nissen 1989). Part of the additional error may be attributable to the effects of unresolved binary systems (see Section 2.4.3). Another problem with the currently practiced formalism may be its calibration to the Fraunhofer deblanketing vectors by Wildey et al (1962), which remain to be checked against the latest stellar atmosphere line lists and opacities (Kurucz 1992). Intermediate band, Strömgren photometry provides greater sensitivity to not only the measurement of abundances, but to age, reddening, temperature, and surface gravities as well for early type stars. The price is a greater demand on photometric precision—errors in the millimagnitude regime are needed. Thus, only recently has *uvbyβ* photometry even been attempted for moderately deep (V $\lesssim 19$), in situ surveys (Croswell et al 1991, von Hippel 1992). At present, *uvbyβ* photometry is having the greatest impact in thin disk (cf Adamson et al 1988 and the AVR studies in Section 1.2.2) and selected surveys (Nissen & Schuster 1991, Laird et al 1988a). The intermediate band, DDO system, which can provide metallicities of 0.25 dex with 1% photometry, has enjoyed popularity as a metallicity discriminator in giant star surveys (Norris et al 1985, Hartkopf & Yoss 1982, Yoss et al 1987, Morrison et al 1990, Morrison 1993). The measurement of metallicities for red dwarfs, either spectroscopically or photometrically, is in a less developed state, but separation of late subdwarfs from their metal-rich counterparts has been demonstrated with combinations of redder passbands (Mould & Hyland 1976, Hartwick 1977, Hartwick et al 1984, Stauffer & Hartmann 1986). Calibration of these various "blue excess" measurements to [Fe/H] awaits the construction of atmosphere models for cool stars which incorporate molecular line libraries and opacities.

2.2.2 SPECTROSCOPIC ABUNDANCES AND RADIAL VELOCITIES With advances in detector technology, extensive libraries of stellar spectra have been compiled in the past decade. Repeated observations of stars make possible systematic searches (Carney & Latham 1987) and the determination of orbits for (Latham et al 1988, 1992) new spectroscopic binaries—a new dimension in population studies (Section 3.2.3). With multifiber spectroscopy deep, in situ surveys may now be undertaken with great efficiency (cf Wyse & Gilmore 1990). A popular moderate (1 Å) resolution abundance indicator is the Ca II K line at 3933 Å, which provides excellent sensitivity for dwarf, giant and HB stars with a large range in color ($0.3 < B-V < 1.1$) and metallicities ($-4.5 < [Fe/H] < -1.0$) (Norris 1980, 1986; Beers et al 1985, 1990; Ratnatunga & Freeman 1985, Ryan & Norris 1991, Morrison 1993). With spectra of signal-to-noise of ~ 10, metallicities with an accuracy of about 0.2 dex and radial velocities with an accuracy of about 15 km s^{-1} can be achieved. Unfortunately, since no single abundance indicator can be universally applied to stars of all metallicities, temperatures, and surface gravity, combinations of spectral features must be used, as in the autocorrelation technique of Ratnatunga & Freeman (1989). A related method for determining 0.2 dex accurate metallicities (and radial velocities) from many lines is that of Carney et al (1987), whereby echelle spectra with signal-to-noise as low as 3 are matched against a synthetic grid of dwarf templates. This technique has been so successful that the Carney et al sample is now regarded as a prime source for dwarf metallicity standards; but note that most of these metallicities have been derived using $\delta(U-B)$ to correct $B-V$ based temperatures for line-blanketing, an uncertain enterprise for $[Fe/H] \leqslant -2$.

2.3 *Proper Motions*

2.3.1 SYSTEMATIC ERRORS IN PROPER MOTION SURVEYS Among the recent kinematically-selected surveys (e.g. Fouts & Sandage 1986, Carney & Latham 1987, Norris & Ryan 1989b, Schuster et al 1993) the primary source for star selection is usually taken to be the LPMS, but, with the hope of improving the astrometry, the proper motions from both the LPMS and NLTT have been averaged. This procedure is beset by three biases, each contributing to systematic overestimates of transverse velocities: 1. Selecting for stars with high proper motions results in a bias towards stars that have measured proper motions (either due to systematic or random errors) higher than their actual value. 2. The LPMS motions are systematically higher than the NLTT motions by $\sim$0.02 arcsec $year^{-1}$, but up to several times more than this for certain proper motion ranges (Luyten 1974). Checks by other authors (Dawson 1986, Cudworth 1990) have found the LPMS motions to be systematically too large. 3. Requiring that a star have motions published in two catalogues with different proper motion limits *ensures* the selection of a preponderance of stars with overestimated proper motions in the catalogue with the larger limit. The consequence of the latter two biases is demonstrated in Figure 1 for a typical sample of stars selected to be in both the NLTT (proper motion limit of 0.18 arcsec $year^{-1}$) and the LPMS (limit of 0.27 arcsec $year^{-1}$). In general the averaged proper motion is larger than the true motion, and the problem is particularly severe for stars with $\mu_{NLTT} \leqslant 0.27$ arcsec $year^{-1}$. More than 75% of the stars in Figure 1 have adopted motions larger than if the NLTT motions had been used alone. This conspiracy of proper motion biases has not yet been modeled, but some of its effects may be subtle. Some kinematical quantities have been overestimated, as shown by Cudworth's (1990) reanalysis of the Galactic escape velocity. On the other hand, the separation of Galactic populations on the basis of, for example, $|W|$ or V

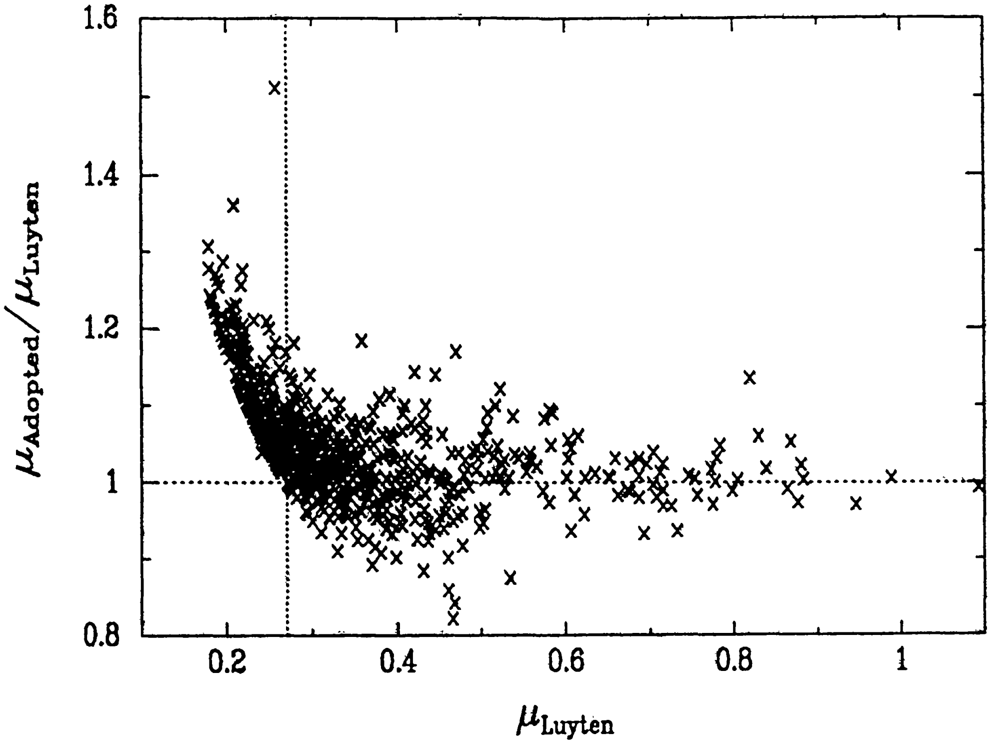

Figure 1 The systematic proper motion bias in a proper motion–selected survey obtained from averaging measures from the NLTT and the LPMS catalogues. The ordinate gives the ratio of the proper motion as adopted (an average of LPMS and NLTT motions) to that from the NLTT alone. Sample shown is from Fouts & Sandage (1986).

(see Sections 3.3 and 3.4) has also been affected and, because stars with smaller motion tend to be farther away, there is some magnitude dependence in the bias.

2.3.2 ABSOLUTE FRAMES OF REFERENCE AND THE SECULAR PARALLAX Compact galaxies can be used as references for the derivation of absolute proper motions and provide important checks on color, magnitude, and positionally-dependent systematic errors in astrometric surveys (Chiu 1980, Majewski 1992a, Guo et al 1993), but do not reach useful densities (~ 100 deg^{-2}) until V $\approx$ 19. Quasars make ideal extragalactic point sources, but have two properties that can lead to astrometric complications—variability and unusual colors—as well as the disadvantage of low density (only ~ 10 deg^{-2} to V $\approx$ 20). Thus small area proper motion surveys must reach deep limiting magnitudes to establish a reference frame. Some advantage may be gained by using Schmidt plates (Taff 1989; Taff et al 1990; Reid 1990, 1992; Soubiran 1992), but with a commensurate loss in astrometric precision due to poorer plate scale. When galaxies and QSOs are inaccessible (e.g. at low Galactic latitudes or bright magnitudes), and there is no way to bootstrap to the extragalactic frame (cf Brosche et al 1991), the correction from relative to absolute proper motion traditionally has relied on secular parallax corrections for faint, presumably distant, field stars, after accounting for the solar apex and differential rotation. Until recently, the secular parallaxes were adopted either from the Yerkes model (van Altena 1974a) or from early results (Klemola et al 1971, Klemola & Vasilevskis 1971) of the Lick Northern Proper Motion (NPM) program with respect to galaxies, but quite different results could emerge from these methods (Cudworth 1976)[6]. It is now possible to take advantage of the improved NPM (Klemola et al 1987; see van Altena et al 1991 for the "SPM") to obtain more reliable corrections from relative to absolute proper motions. For example, Cudworth & Hanson (1993) have recently used a Galactic model (van Altena et al 1988, van Altena & Lee 1989) that includes an IPII as well as improved NPM estimates (Hanson 1989) of the solar motion to derive reliable space velocities for 14 nearby ($\leqslant 11$ kpc) globular clusters. For objects at larger distances, however, only the method of absolute proper motions with respect to extragalactic objects has been applied reliably (Majewski 1992a, Schweitzer et al 1992, Guo et al 1993, Majewski & Cudworth 1993).

2.4 *Distances*

Even in the most recent solar neighborhood surveys, very few of the stars have reliable trigonometric parallaxes. Thus a great deal depends on the accuracy of the absolute magnitude calibration to color, luminosity, age, and abundance; the fractional error in a derived photometric/spectroscopic parallax distance, and, in turn, the transverse velocity, depends on the error, σ_M, in the adopted absolute magnitude as 0.46 σ_M.

2.4.1 POPULATION I MAIN SEQUENCE CALIBRATION In general, the Population I main sequence is adopted either from the zero age main sequence (ZAMS) determined from solar metallicity trigonometric parallax stars or as the color-absolute magnitude sequence defined by the Hyades cluster. The two are not the same, since the Hyades has [Fe/H] ≈ 0.20. The UBV method of photometric parallax determines the "subdwarfness" of a star with respect to the Hyades $M_V(B-V)$ locus based on ultraviolet excess

[6] The Yerkes model was not tied fundamentally to extragalactic objects, but rather to transit circle data, so that its precision was subject to the accuracy of the measured precession. Moreover, since data for faint ($V > 16$) stars were lacking at the time of its construction, the model did not include an IPII component, which is a major contributor to the field in the range of magnitudes covered. On the other hand, some systematic errors in the pilot Lick program have also since been identified and removed.

(Section 2.2.1; Wildey et al 1962, Sandage 1969). The *uvbyβ* system is similarly defined (Crawford 1975). Thus, it is significant that the most recent work on the Hyades distance has resulted in, on average, greater distances than before. Summaries of the methods of Hyades distance determination are in van Altena (1974b), Heck (1978), Rowan-Robinson (1985), and Schwan (1990). Hanson (1980a) summarized the various astrometric techniques to that point, and derived a weighted mean distance modulus of 3.30 ± 0.04, which has since become the "standard value," although some adherents still use the earlier value of 3.03 by van Bueren (1952). Improved Hyad radial velocities (Griffin et al 1988) and proper motions (e.g. Schwan 1991), as well as the identification of new Hyads (Reid 1992), has allowed new attempts at the convergence point method, yielding distance moduli of 3.42 (Loktin et al 1986), 3.28 (Gunn et al 1988), 3.40 ± 0.04 (Schwan 1991), and 3.40 (Reid 1992). Recent photometric comparisons between the Hyades and trigonometric parallax stars have yielded 3.40 (Hauck 1981), 3.30 (Eggen 1982), and 3.26 (Cameron 1985). The method of dynamical parallaxes of binary systems consistently gives high values—3.30 (Hardorp 1980), 3.47 (McClure 1982), 3.36 (Peterson & Solensky 1987), 3.35 (Heintz 1988). In fact, VandenBerg & Bridges (1984) have argued that the distance modulus must be $3.40 \leqslant m-M \leqslant 3.50$ in order to avoid serious disagreement between observed and theoretical mass-luminosity relations. But, as they point out, this conclusion is based on still uncertain values for the solar B−V color (which has measured values $0.62 \leqslant \mathrm{B-V} \leqslant 0.68$), the Hyades [Fe/H] (still uncertain to 0.1–0.2 dex), and the Hyades helium abundance, among other problems (see also Hardorp 1980). Note also that the trigonometric parallax work of Upgren et al (1990) and Patterson & Ianna (1991) each give 3.30 ± 0.10 for a total of 33 stars (when each is calibrated to the same absolute parallax system). In summary, it is possible that the actual value of the Hyades distance modulus may be as large as 3.40. If so, then the distance scales in surveys calibrated to the Hyades would be systematically underestimated by 5–19% (Figure 2).

In principle, the issue of the Hyades distance modulus can be avoided through use instead of trigonometric parallax stars with [Fe/H] = 0.0. However, parallax stars encompass a range of ages, a property which can be difficult to determine for a star in isolation, yet which, by definition, affects a determination of the ZAMS. The accuracy of the derived sequence is also dependent on the accuracy of the measured abundances (iron, helium, ...) for each star. Note also the following possible biases which may affect absolute magnitude calibrations using trigonometric parallax stars (cf Hanson 1980b, Gliese 1986): 1. some parallax samples are proper motion-selected, which gives preference to stars below the main sequence,

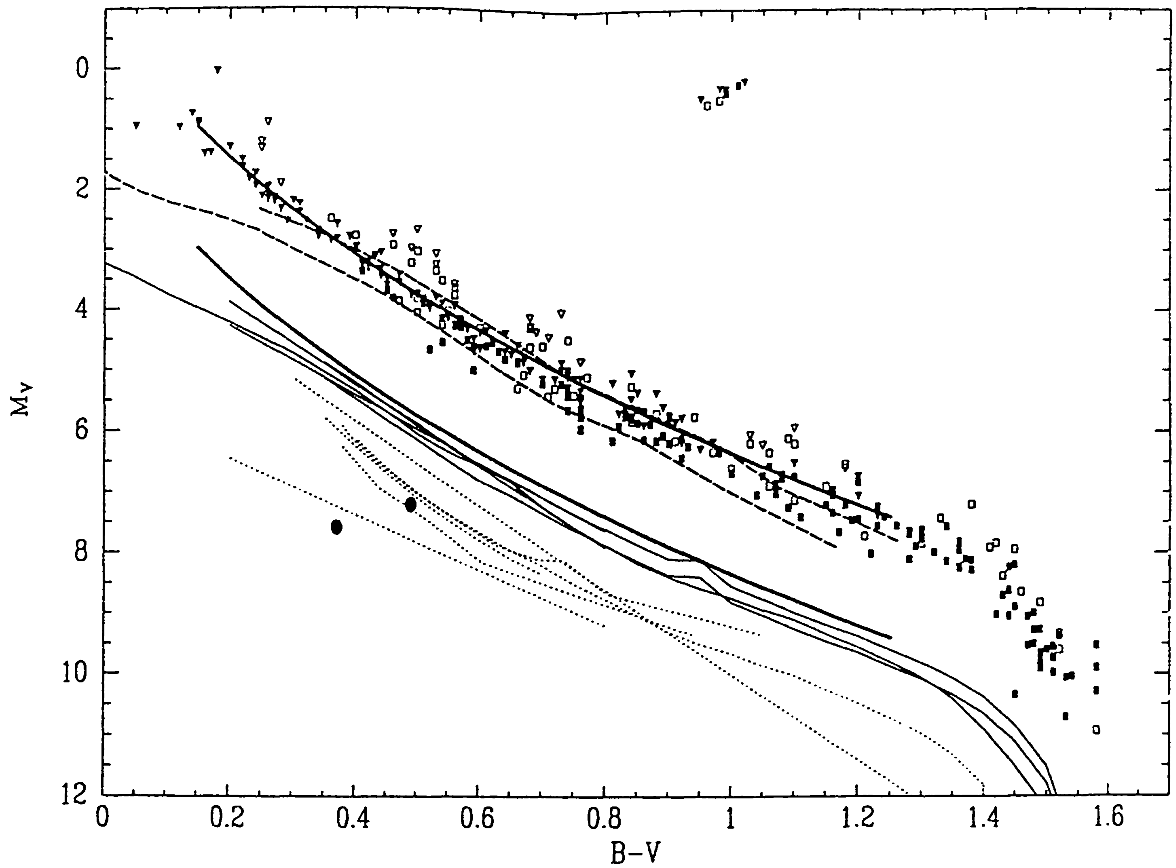

Figure 2 A sampling of adopted color-absolute magnitude sequences for the Hyades and metal-poor stars. The Hyades data from Schwan (1990, 1991) are shown as triangles, and the data from Griffin et al (1988), after subtracting their distance modulus of 3.28 and ignoring cluster depth effects, are shown as squares. Open triangles and squares designate spectroscopic binary members in each sample. The thick solid line shows Schwan's (1991) best fit analytic expression for the Hyades. The dashed lines show the theoretical isochrones derived by VandenBerg & Bridges (1984) for [Fe/H] = 0.0 (lower line) and [Fe/H] = +0.4 (upper line), assuming a solar B−V = 0.66. The remaining analytic functions have been offset by +2.0 magnitudes for clarity: The thin solid lines show the various Hyades color-absolute magnitude relations which have been adopted by recent Galactic structure surveys (Norris et al 1985, Sandage & Kowal 1986, Wyse & Gilmore 1986 after Chiu 1980, Laird et al 1988a, Majewski 1992a) compared to the analytical relation of Schwan (1991; *thick solid line*). Also shown (*dotted lines*) are the absolute magnitudes that would be assigned in various surveys for stars with [Fe/H] = -2.2 ($\delta_{0.6}$ = 0.28). Data are taken from the following sources: Norris et al (1985; a single relation is used for all stars with [Fe/H] < −1), Kuijken & Gilmore (1989) and Wyse & Gilmore (1986; both use Chiu's [Fe/H] = −2.2 sequence for all metal-poor stars), Laird et al (1988a), Sandage & Kowal (1986), Casertano et al (1990; a single relation for all metal-poor stars), Majewski (1992a). The two very metal-poor stars with good parallaxes (van Altena et al 1988) are shown for comparison as solid circles : HD 84937 (B−V = 0.37, [Fe/H] = −2.03), and HD 140283 (B−V = 0.49, [Fe/H] = −2.60). Note that the latter star now appears to be a subgiant (cf Gilroy et al 1988.)

2. preferentially choosing stars with large parallax gives a bias toward stars with positive random parallax error, resulting in a calibration systematically too low in luminosity (Trumpler & Weaver 1953), and 3. the Malmquist (1936) effect will bias magnitude-limited samples in a way that depends on any other imposed selection criteria (Lutz 1986). The imminent publication of both the *Yale General Catalogue of Trigonometric Parallaxes* (cf van Altena & Lee 1989) and the *Third Catalogue of Nearby Stars* (Gliese & Jahreiss 1989) promises some gains on this front. A preliminary melding of these two catalogues to calibrate $M_V(B-V)$ and $M_V(R-I)$ for late type stars has already been attempted (Jahreiss & Gliese 1989).

2.4.2 ABSOLUTE MAGNITUDES FOR METAL-POOR DWARFS Sandage (1986) has reviewed the theoretical basis for Population II main sequence subluminosity. The need for trigonometric parallaxes for subdwarfs is as great as ever. Less than a dozen stars (van Altena et al 1988, Laird et al 1988a) with [Fe/H] < -1.5 and reliable trigonometric parallaxes (usually taken to mean $\sigma_\pi/\pi \leqslant 0.20$ in order to minimize systematic errors of the type described by Lutz & Kelker 1973) have been used in the definition of the most recently adopted metal-poor $M_V(B-V)$ relations. New parallax determinations by Upgren et al (1992) and Monet et al (1992) have made available data for another two dozen metal-poor stars, and large numbers of subdwarf parallaxes are anticipated from the *HIPPARCOS* satellite. Curiously, the situation for stars with [Fe/H] ≈ -1.0, has not improved as substantially (but see Lutz et al 1988). Note that better M_V (B$-$V, [Fe/H]) calibration for Population II stars depends not only on improved trigonometric parallaxes, but better [Fe/H] and age determinations for these stars as well. The traditionally poor definition of the subdwarf main sequence is reflected in the plethora of strategies adopted for dealing with metal-poor stars in surveys over the past decade (Figure 2), with differences that translate to up to a magnitude in distance modulus.

2.4.3 APPLICATION OF THE PHOTOMETRIC PARALLAX METHOD In the absence of luminosity class information, it is customary to assume that photometric parallax stars are zero age dwarfs; this yields the most conservative estimates in distance and transverse velocity. It is often ignored that a significant fraction of these stars have underestimated distances and kinematics. Recent analyses (Carbon et al 1987, Laird et al 1988a, Reid & Majewski 1992) of halo field stars and globular cluster luminosity functions derive ratios of subgiants ($2 \leqslant M_V \leqslant 4$) to main sequence turnoff stars ($4 \leqslant M_V \leqslant 6$) of 5–14%, depending on metallicity. However, a magnitude-limited survey will sample a much larger volume for subgiants; Croswell et al (1991), using *uvbyβ* photometry to determine luminosity classes, measure dwarf:subgiant:giant ratios of 1:0.2:0.2 for their sample of V < 16

stars. On the other hand, since more distant stars have smaller proper motions, the selected sample of Laird et al (1988a) is only $\sim 10\%$ subgiants. The presence of unresolved binary systems can also significantly alter calculated distance moduli. In fact, a common method to search for unresolved binaries is to compare distance moduli from photometric parallax determinations using different color combinations (Carney 1983), or through comparison of distance moduli determined for common proper motion pairs (Weis 1991, Ryan 1992). The Population I binary fraction is around 50% (Duquennoy et al 1991, Kroupa et al 1991, Reid 1991, Weis 1991). Determinations of the halo binary fraction consistently find values of 20–30% (Carney 1983, 1993; Stryker et al 1985; Lu et al 1987; Ryan 1992). Less attention has been given to determining the IPII binary fraction, but it is likely to be somewhere between 20 and 50%.

Comparisons (Gliese 1986, Ryan 1992) between UBV photometric parallaxes and those using longer wavelength bandpasses have shown a larger dispersion in M_V error for the UBV parallaxes. This may reflect, partly, the facts that 1. the UBV method is more sensitive to the detailed abundance patterns in blue stars than are red passbands; 2. blue bands are more sensitive to reddening errors; 3. $B-V$ saturates for red stars where the steep $M_V\,(B-V)$ relation leads to greater M_V errors for a given color error; and 4. the subdwarf/metal-rich separation is smaller in color-magnitude diagrams that use redder passbands. More serious may be the finding by Ryan (1992) who, by comparing UBV, VRI, and trigonometric parallaxes, found UBV distances to be $\sim 16\%$ overestimated, but it is not clear how much his trigonometric parallaxes should be adjusted by Lutz-Kelker corrections (Hanson 1979); earlier experiments (Gliese 1986, Laird et al 1988a) demonstrated no clear systematic differences between UBV, VRI, VJK, and trigonometric parallaxes.

2.4.4 RR LYRAE STARS RR Lyrae distances are critical not only to studies of Galactic populations, but as an independent check on the extragalactic distance scale as well. They also play a pivotal role in globular cluster age-dating (Section 3.2.2): After reliably setting cluster distances, ages may be derived from the main sequence turnoff luminosity. These analyses are complicated by the fact that M_V for an RR Lyrae star is dependent not only on its evolutionary state relative to the zero-age HB, but also on its metallicity. Unfortunately there have been considerable differences in the derived relations $\langle M_V(\mathrm{RR})\rangle = a\,[\mathrm{Fe/H}]+b$ that translate to significant variations in the distribution of derived cluster ages. Five methods have been applied to the determination of $M_V(\mathrm{RR})$, and account for a factor of two range in derived slopes a: 1. main sequence fitting of globular clusters (Buananno et al 1989, Sandage & Cacciari 1990, $a = 0.37 \pm 0.14$), 2. analysis of the period-shift effect (Sandage 1990b, $0.19 \leqslant a \leqslant 0.39$; Sandage & Cacciari 1990, $a = 0.39$; Fernley 1993, $a = 0.19$), 3. the Baade-Wesselink method (Cacciari et al 1989, $a = 0.17 \pm 0.05$; Liu & Janes 1990, $a = 0.20 \pm 0.06$; Longmore et al 1990, $0.16 \leqslant a \leqslant 0.32$; Jones et al 1992, $a = 0.16$), 4. the variation with [Fe/H] of the red giant bump in cluster luminosity functions (Fusi Pecci et al 1990, $0.15 \leqslant a \leqslant 0.20$; Sarajedini & Lederman 1991, $a = 0.15 \pm 0.15$), and 5. statistical parallax studies of field RR Lyrae stars (Hawley et al 1986, Strugnell et al 1986). The latter studies find no clear evidence for $a \neq 0$, but are also most subject to small number statistics. Carney et al (1992) reanalyze the various techniques; they claim somewhat better agreement between them, and derive the average relation $\langle M_V(\mathrm{RR}) \rangle = 0.15(\pm 0.01)[\mathrm{Fe/H}] + 1.01(\pm 0.08)$, but the situation is apparently still uncertain (cf Sandage 1993; also Catelan 1992).

3. STATUS OF THE KEY OBSERVABLES

3.1 *The Extent of Intermediate Population II*

Simply observing a kinematic or abundance gradient is not sufficient to distinguish between models (Section 1)—the gradient may either be intrinsic to a single stellar population or the result of population overlap. Thus, knowing the spatial extent of Galactic components is vital before claims of gradients may be critically assessed.

Reid & Majewski (1993) summarize previous studies of the disk, IPII, and halo density parameters. In general, there is greater consistency among groups that derive structural parameters via self-consistent, simultaneous modeling of all Galactic components than among studies that focus on tracers of single, specific components (though how much this consistency is driven by habit or necessity is unclear). For example, attempts to derive the local halo to disk density through studies of high velocity stars (Section 2.1.2) give ratios from 0.11–0.32%, while the various starcount models find a smaller range of 0.1–0.2%. Studies of RR Lyraes by Hawkins (1984), Saha (1985), and Kinman (1992) and of globular clusters by Zinn (1985) have derived halo density distributions, $\rho \propto r^{-\nu}$, with slopes $\nu = 3$, 3.1, 3.5, and 3.5 respectively, while starcount models consistently adopt de Vaucouleurs (1977) $r^{1/4}$ spheroids with an effective radius of 2.7 kpc. The degree of halo flattening is much debated. Kinman (1965) and Kinman et al (1966) found evidence for flattening in the inner halo, and since then other studies (Hartwick 1987, Wesselink 1987, Wyse & Gilmore 1989, Sommer-Larsen & Zhen 1990, Schuster et al 1992, Zinn 1992; see Section 6 of Freeman 1987) have suggested that at least some part of the halo may be flattened, with c/a as low as 0.4. However, most starcount studies have been successful fitting a single halo component having $0.8 \leqslant c/a \leqslant 0.9$.

The thin disk parameters are generally thought to be well understood: Disk stars with $M_V > +4$ are dominated by a population older than ~ 3 Gyr, and starcount models have successfully fit them with $\geqslant 325$ pc scaleheight exponentials. It is disquieting then that the K dwarf photometric parallax study by Kuijken & Gilmore (1989) yielded a scaleheight as low as 249 pc.

The wide range of density parameters that have been derived for IPII (see summary in Reid & Majewski 1993) reflects the difficulty in disentangling its kinematical, chemical, and spatial overlap with the halo and thin disk. The first modern IPII characterization (Gilmore & Reid 1983) yielded a 1450 pc scaleheight and 2% local normalization with respect to the thin disk. Bahcall (1986) criticized this result—partly on the grounds that the contributions of the halo had been ignored—and argued that no IPII was evident. But further evidence for an IPII has prevailed, albeit usually with less global significance than implied by Gilmore & Reid. Note that with local samples, the density normalization and scaleheight are anticorrelated when fit simultaneously; Figure 3 shows the effects of varying these two parameters (for representative values in the literature) within the context of a fixed set of halo and thin disk characterizations. However, Reid & Majewski have fit the deep ($V > 21.5$) NGP star counts and colors from Majewski (1992a) and Kron (1980) and found an IPII scaleheight of 1400–1600 pc and local normalization of 2.5–2.0%. They also reanalyzed the brighter Gilmore & Reid SGP data with an improved color-magnitude relation and in the context of a model that included a halo component (the earlier neglect of halo stars was determined to have a negligible effect): Scaleheights and normalizations were found to range from 1300 pc and 2.2% for the bluest stars ($4.5 \leqslant M_V \leqslant 5.5$) to 1720 pc and 3.3% for the reddest stars ($6.5 \leqslant M_V \leqslant 8.5$). Such an IPII would make up $\sim 10\%$ of the total disk mass. These models assumed a constant $[Fe/H] \approx -0.4$ for all IPII stars. The introduction of IPII metallicity gradients produces even *larger* scaleheights *and* normalizations: ~ 2540 pc and 3.65%, respectively with $\partial[Fe/H]/\partial Z = -0.25$ dex kpc^{-1} (Yoss et al 1987) for $6.5 \leqslant M_V \leqslant 8.5$ stars. On the basis of a halo/IPII division via the distribution of asymmetric drifts, Majewski's (1992) stars at 1.25 kpc $\leqslant Z \leqslant 8$ kpc are consistent with an IPII scaleheight of ~ 1400 pc and normalization of $\sim 3.8\%$. Rodgers (1991) has identified metal-rich ($[Fe/H] > -1.2$) RR Lyraes exclusively with IPII, and finds a 1.5 kpc scaleheight. Hartwick (1987; see also Kinman 1965) found his sample of metal-*poor* ($[Fe/H] \leqslant -1.0$) RR Lyraes best described with a two-component model, one spherical and another flattened with an effective scaleheight of 1.6 kpc (the latter consistent with the distribution of $[Fe/H] < -1$ globulars at $R < 8$ kpc). σ_W for IPII is typically found to be ~ 45 km s^{-1} (Hartkopf & Yoss 1982, Sandage &

Fouts 1987, Schuster et al 1993; but see Section 3.3.1); by Kapteyn's (1922) method (cf Sandage 1981) this implies a scaleheight $\geqslant 1400$ pc. Such extensive IPII components are also characteristic of M31 and other galaxies (Wyse & Gilmore 1988).

How is it that the other studies have tended to find less substantial IPIIs? A number of new lines of evidence suggest that IPII is more kinematically and chemically extensive than has been appreciated heretofore, and a large fraction of IPII stars may often go unrecognized. For example, IPII stars with disk kinematics and yet as metal poor as -1.6 dex or less (Section 3.4.2) have now been identified. Morrison et al (1990) estimate this population to make up about 80% of the $-1.0 \geqslant$ [Fe/H] $\geqslant -1.6$ stars at $Z = 0$. They found a scaleheight of 1.5 ± 0.7 kpc for these stars, and, more recently (Morrison 1993), 2.0 kpc for a sample at $4 \leqslant r \leqslant 7$ kpc (but see von

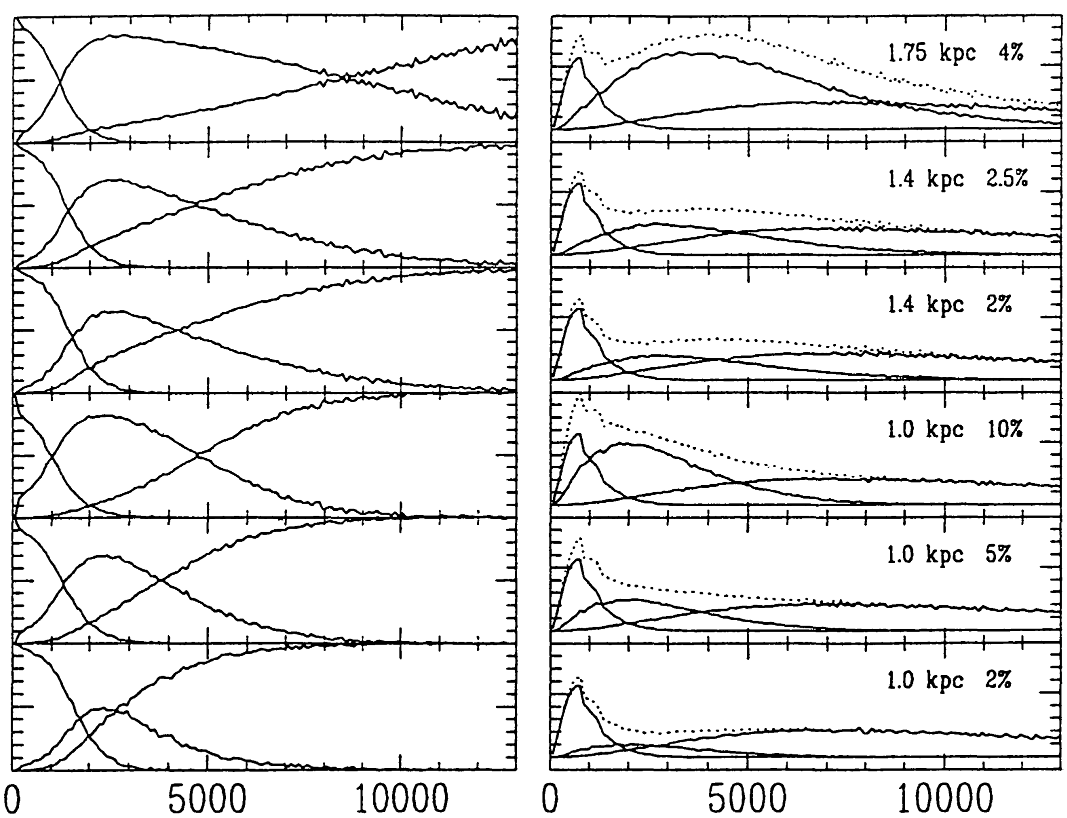

Figure 3 Three-component starcount models with IPIIs of varying scaleheight and local normalization with respect to the thin disk. The left panels show the relative fractions of thin disk, IPII, and halo stars as a function of $|Z|$ for an observing cone directed at a Galactic pole; the right panels show the relative numbers for each component and their sum (*dotted line*). Models were calculated for G dwarfs with the parameters of the "interim model" described in Reid & Majewski (1993).

Hippel & Bothun 1993). Sommer-Larsen & Zhen (1990) have found their "intermediate weak" sample with $-1.2 \geqslant [Fe/H] > -1.5$ to contain a significant fraction of IPII stars. Within their "very metal-poor" ($[Fe/H] \leqslant -1.5$) sample, they also identified a "highly flattened *halo*" component, confined to $|Z| < 3$ kpc and contributing 40% of the local metal-poor density. It is likely that their flattened "halo" component reflects additional IPII contamination of their very metal-poor sample. The *disk* globular clusters M28 and M107 with $[Fe/H] \leqslant -1.0$ (Section 2.1.3) represent globular cluster equivalents of the IPII metal-weak tail. IPII stars also vary greatly in asymmetric drift and velocity dispersion, depending on Z. (See Section 3.3.1).

Thus, IPII may dominate tracer and in situ surveys to $Z = 5$–8 kpc (Figure 3), and contribute as much as 25% to unbiased stellar samples at $Z = 7$–12 kpc. Recognition of this spatial overlap has direct bearing on the analysis of gradients and other properties of the various components.

3.2 *Ages and Age Gaps*

3.2.1 THE AGE AND STAR FORMATION HISTORY OF THE DISK *Open cluster ages* A 10 ± 1 Gyr age for NGC188 (VandenBerg 1985) has long been regarded as representative of the oldest disk stars, but a 12.5 Gyr age has been found for NGC 6791 (Janes 1988, Kaluzny 1990). This would give a disk age near to that of the young globular cluster 47 Tuc—13.5–14 Gyr (Hesser et al 1987; Section 3.2.2)—but ages 3–5 Gyr smaller have also been determined for these two open clusters in recent analyses (Twarog & Anthony-Twarog 1989, Grenon 1990, Demarque et al 1991b). The disparity in open cluster ages partly reflects the critical dependence of cluster isochrone fitting on the adopted reddening (often large for open clusters); even small reddening errors can create significant errors in the derived age and metallicity. However, Hobbs et al (1990) have circumvented the problems of having to determine reddenings, colors, or distances for cluster stars; they determine effective temperatures and metallicities for cluster turnoff stars directly through echelle spectroscopy. Their technique, which is free from systematic errors and subject only to uncertainties in the model atmospheres, yields significantly smaller open cluster ages—7.7 ± 1.4 Gyr for NGC 188 and 5.2 ± 1.0 Gyr for M67 (Hobbs & Thorburn 1991)—which imply a wider thin disk/IPII age gap.

That both old clusters NGC 188 and NGC 6791 are near solar metallicity is generally regarded as a demonstration of the large scatter in the mean Galactic AMR (cf Geisler 1987), similar to that observed in the F-G dwarf studies (cf Section 1.2.2; GWK). However, Marsakov et al (1990) point out that the detailed cluster and field star age-metallicity distributions show some dramatic differences, especially for $[Fe/H] < -0.3$. Apparently, [Fe/H] < -0.3 stars are not presently formed in the field but are formed very efficiently in open clusters. The overwhelming skew of the open cluster age distribution towards ages less than 1 Gyr may be related to a recent overall increase in the SFR (see below) as well as the timescale for cluster destruction, and also implies that ancient open clusters like NGC 188 and NGC 6791 are quite extraordinary.[7] Fortunately, a variety of techniques have been developed for determining the age of Galactic disk stars *directly*.

White dwarf luminosity function D'Antona & Mazzitelli (1978) first demonstrated that the finite age of the Galactic disk would lead to a cutoff in the local white dwarf luminosity function for $L < \sim 10^{-4}\ L_{\odot}$, and a sharp decline in the number of intrinsically faint white dwarfs was verified by Liebert et al (1979). Since then, increasingly sophisticated models (Winget et al 1987, Iben & Laughlin 1989, Yuan 1989, Noh & Scalo 1990, Wood 1992) which incorporate improved cooling functions, a variety of composition models, and which test for evolutionary changes in the IMF, SFR, and disk scaleheight have been applied to improved luminosity functions (Liebert et al 1988). Most of the derived disk ages are consistent with Wood's (1992) best estimate, obtained after extensive reanalysis of a wide range of variables and utilizing new cooling curves: 7.5–11 Gyr, with extreme limits of 6–13.5 Gyr. The greatest source of errors affecting this analysis are uncertainties in the core composition, mass of the surface helium layer, and the bolometric correction for cool white dwarfs. A complication which remains to be incorporated into the models is possible additional heating due to the settling of neon into the core during solidification, which may delay cooling by 2 Gyr (Isern et al 1991). The small number of white dwarfs (cf Hintzen et al 1989) that presently tie down the critical faint end of the luminosity function is also of great concern.

Nucleocosmochronology Butcher (1987) has found no evolution in the line strength ratios of the long-lived (half-life 14 Gyr) isotope ^{232}Th to the stable element Nd in a sample of 21 G dwarfs with a wide range in ages, and thus determined the age of the disk to be <9.6 Gyr. Radioactive dating of transuranic elements in the solar system by Fowler & Meisl (1986) and Fowler (1987) has established the duration of Galactic nucleosynthesis prior to formation of the solar system to be 5.4 ± 1.5 Gyr, giving a disk age of 10.0 ± 1.5 Gyr. Both of these results have been contested. In the former case, the assumptions regarding the assumed relative rates of *r*-

[7] On the basis of its age, Janes (1988) suggests that there may be no compelling reason to classify NGC 6791 as an open cluster, and proposes, instead, that it may be a disk globular cluster.

and *s*-processes has been questioned (Clayton 1988). The latter calculation has been debated both on the grounds that it was made in a simplified "closed-box" scenario and that the influence of even modest infall will have disturbed the isotope ratios, and on the grounds that additional *r*-process reactions (namely beta-delayed fission) will lower production ratios (Cowan et al 1987, Clayton 1988). These critics revise the most likely disk age to >12 Gyr (but see Fowler 1987).

Stellar chromospheric activity and the history of star formation in the disk The age of the nearby Galactic disk should be written in the record of star formation history in the solar neighborhood. Through a variety of ingenious techniques, it is possible to view this history with greater resolution than ever before. The new focus reveals a very irregular star formation history with evidence for SFR fluctuations of an order of magnitude. The strongest evidence comes from Barry's (1988) derived ages for a volume-limited sample of 115 F–G stars using the strength of Ca II H and K emission, which is a function of chromospheric activity and declines with age. Several important features are seen in the star formation history derived from Barry's age distributions† (Figure 4; Noh & Scalo 1990): 1. a major star formation epoch from 11 to 7 Gyr ago (referred to here as "burst C"), 2. a local SFR minimum at ~ 6.5 Gyr, 3. a major star formation burst ("burst B") starting about 6 Gyr ago and declining to a significant SFR gap ~ 3 Gyr ago, and 4. a burst peaking in the last 0.5 Gyr ("burst A"). The oldest nearby stars formed ~ 13 Gyr ago, but the first low velocity stars apparently formed 11 Gyr ago.[8] Note that the SFR gap at age 3 Gyr was found in an earlier Ca II survey by Vaughan & Preston (1980).

† ADDED IN PROOF: The author has been made aware of the work by Soderblom et al (1991) which cautions that the case against a constant star formation rate is not yet conclusive on the basis of HK emission dating. Several objections are raised concerning the Barry (1988) data and analysis which, they argue, may be premature to trust. This difference of opinion stems primarily from 1. a preference by Soderblom et al to analyze the age data in a cumulative distribution (which tends to smooth features seen in differential distributions such as Figure 4), and 2. the form of the adopted age-activity law—a simple power law (Barry) versus a more complicated form "constrained to (give) a constant star formation rate" (Soderblom et al) and with particular emphasis towards reducing the apparent SFR spike within the last 1 Gyr. But the form of the latter age-activity relation is a power law for stars older than ~ 2 Gyr, which Soderblom et al show to yield the same features for their own data as Barry found for his stars. Moreover, various other evidence cited in the text corroborates the features in Figure 4.

[8] Note that the age scale is calibrated to an 8 Gyr age for NGC 188 and a 4 Gyr age for M67, and so is subject to a 20–30% uncertainty depending on isochrone fitting to these clusters. With a 10 Gyr age for NGC 188, the first low velocity stars form at 13 Gyr. Note that the 12–13 Gyr spikes come from only a few survey stars to which Noh & Scalo have applied scaleheight and evolutionary corrections.

According to Scalo & Miller (1980; Scalo 1987) the frequency distribution of Lithium abundances in red giants (Brown et al 1989) can be interpreted in terms of a star formation gap 3 Gyr ago as well as a burst from 7 to 4 Gyr ago, while Scalo (1987) has interpreted features at ~ 1.2 and 3 $M_{\odot}$ in the present day mass function as signatures of starbursts 5–6 and 0.3 Gyr ago [see also Gomez et al (1990) for support of these features from stellar kinematic data]. Marginal features in the white dwarf luminosity function are consistent with the SFR peaks at 0.3 Gyr and 1.8 Gyr ago in Figure 4 (Noh & Scalo 1990, Wood 1992). Note also that the time resolution of an SFR study is intrinsically limited by the sample size and age uncertainties, so that the derived SFR history (for example, Barry's) is smeared to some unknown extent. An example of the effect of such smearing is shown in Figure 4. The Twarog (1980) *uvbyβ* data on F and G stars—which are often cited as evidence for a *constant* SFR, in spite of their showing a rise at ~ 4 Gyr—are well matched by coarser binning of the Barry data (Barry and Noh & Scalo discuss possible problems in the Twarog analysis which may account for the discrepancy at small ages). Meusinger's (1991) reanalysis of the F and G star data is also consistent with an enhanced SFR earlier than 4 Gyr ago.

The features in Figure 4 are *global* in the sense that they apply to all disk stars with orbits that carry them through the solar neighborhood (annuli 2–5 kpc wide for orbital eccentricities of 0.1–0.3, respectively). The metallicities for Barry's stars are narrowly distributed about $[Fe/H] \approx -0.1$ or -0.2, but burst C shows a metal-weak tail to $[Fe/H] \approx -0.7$. Marsakov et al (1990) have analyzed a sample of 5500 nearby F stars and concluded that a breakdown in the generally continuous relationships between age, metallicity, and kinematics at about 2–3 Gyr is consistent with the suggestion by the Barry data that the old thin disk formed in bursts B and C. (They also find evidence for a SFR depression ~ 6 Gyr ago). With kinematic data from Woolley et al (1970), one finds that Barry's stars exhibit a sudden jump to a hotter distribution and larger mean orbital inclination between bursts A and B, but little change in the total mean peculiar velocity and dispersion between bursts B and C. The derived AVR is similar to the evolution found by Carlberg et al (1985; Section 1.2.2), with a "saturation" setting in for stars older than ~ 5 Gyr (albeit at a smaller asymptotic value than Carlberg et al), while the evolution from $\sigma_V/\sigma_U = 0.5$ to unity is reminiscent of that found by Knude et al (1987).

3.2.2 THE AGE OF THE HALO *Globular cluster age dating* Good reviews of globular cluster age-dating are by Bolte (1990, 1993), Demarque et al (1991a), Renzini (1991), and VandenBerg (1991). In principle the mean

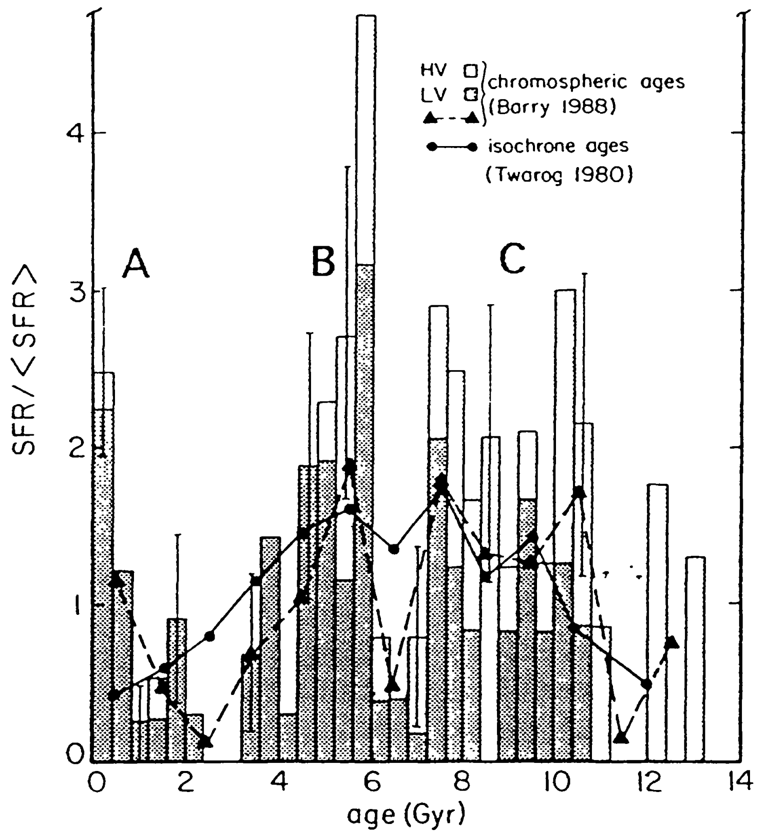

Figure 4 The history of the SFR in the Galactic disk as derived by Noh & Scalo (1990) from the age distribution of Barry (1988) based on chromospheric emission in a volume-limited sample of nearby stars. The Barry data (*histogram*) have also been smoothed to 1 Gyr resolution (*triangles*) for comparison to the work by Twarog (1980). Shaded and unshaded regions correspond to low and high velocity stars, respectively, where these authors define high velocity as $(U^2+V^2)^{1/2} \geqslant 65$ km s^{-1} or $|W+10| \geqslant 30$ km s^{-1}. (Adapted from Noh & Scalo 1990.)

age of the halo globular clusters sets the time of halo formation, while the existence of any cluster age range defines the rate of formation. The former is more difficult to determine since absolute ages depend critically on accurate determinations of cluster [Fe/H] and [O/H] as well as distance moduli, which must be known to 0.10 accuracy to achieve a 10% precision in age (Sarajedini & King 1989, Sandage & Cacciari 1990, Carney et al 1992). It is now clear that the halo subdwarfs are enhanced in oxygen with respect to the sun, but whether [O/Fe] remains constant for all [Fe/H] less than some particular value—typically around -1.0 dex (Wheeler et al 1989) but perhaps as low as -1.7 dex (see Bessell et al 1991)—or shows a variation with [Fe/H], as suggested by Abia & Rebolo (1989), is still not adequately resolved (see the reviews by Barbuy 1992, Pagel 1992). The variance of results may be related to the use of permitted versus forbidden lines (Barbuy & Erdelyi-Mendes 1989, Bessell et al 1991, Spite 1992). Under the assumption that halo field dwarfs are similarly enhanced to cluster dwarfs, as suggested by the similarities between field and cluster giants (Sneden et al 1991, Kraft et al 1992), cluster ages have been calculated under a variety of scenarios. With $[O/Fe] = 0.3$ and $\partial M_V/\partial[Fe/H] = 0.15$ for RR Lyraes (Section 2.4.4), Carney et al find a cluster AMR from 20 Gyr ages for $[Fe/H] \leqslant -2.0$ clusters to 15 Gyr ages for clusters with $[Fe/H] \geqslant -1.3$ (with age uncertainties of about 3 Gyr per cluster). But adoption of a rather steep enhancement relation, $[O/Fe] = -0.42\ [Fe/H]+0.22$, consistent with the Abia & Rebolo data, leads to a compression of the age scale which diminishes the AMR and lowers the mean cluster age to 14.3 ± 2 Gyr with a scatter of about 4.5 Gyr. Sandage & Cacciari find an AMR extending from 18 to 14 Gyr with $\partial M_V/\partial[Fe/H] = 0.19$, with only a weak dependence on the nature of the oxygen enhancement. In the most likely scenario of a relatively constant [O/Fe] enhancement and a smaller $\partial M_V/\partial[Fe/H]$ consistent with the Baade-Wesselink analyses (Section 2.4.4), the above studies arrive at a mean cluster age of ~ 17 Gyr, an obvious AMR, and a minimum globular cluster age of ~ 14 Gyr, discounting the clusters Pal 12 and Rup 106, which have recently been proposed as having been stripped from the Magellanic Clouds (Lin & Richer 1992). Thus, it appears that there is a distinct age gap between the bulk of the globular clusters (including the disk globular 47 Tuc) and the thin disk. However, before making this conclusion, note that: 1. In the case of $\partial M_V/\partial[Fe/H]$ as high as 0.39, the AMR flattens out (or even switches slope) and the minimum globular cluster age becomes 12 Gyr (Sandage & Cacciari). 2. The diffusion of helium, which has not been accounted for in the above studies, may reduce derived cluster ages by 10–30% (Noerdlinger & Arigo 1980, Stringfellow et al 1983, Deliyannis et al 1990, Profitt & Michaud 1991), although Chaboyer et al (1992) find the effect to be less than 0.5 Gyr (see also Deliyannis & Demarque 1991). 3. New developments in convection theory (Canuto & Mazzitelli 1991) suggest that the process is more efficient than in standard mixing length theory, and would lead to additional reductions in cluster age estimates.

On the other hand, it can be said with certainty that there does exist an age spread in the globular clusters of at least 3 Gyr. This has been verified through careful *differential* studies of clusters with similar metallicities, a technique free from many of the previous observational difficulties (see Bolte 1993), and which can yield relative ages to better than 1 Gyr. Examples of this work are the studies of "second parameter pairs"—clusters with similar [Fe/H] but different HB morphologies—which find the pair NGC 288 and NGC 362 to be separated by 3 ± 1 Gyr (Bolte 1989, Green & Norris 1990, Sarajedini & Demarque 1990), Rup 106 to be 3 ± 2 Gyr younger than NGC 6752 (Buonnano et al 1990, 1993; DaCosta et al 1992), and Pal 12 to be 25–30% younger than M 5 and NGC 104 (Gratton & Ortolani 1988, Stetson et al 1989). A more generalized and refined technique (Sarajedini & Demarque 1990, VandenBerg et al 1990) measures the color difference between the main sequence turnoff and the base of the red giant branch. VandenBerg et al corroborate the age-metallicity data of Carney et al: a small age dispersion for clusters with $[m/H] \approx -2.1$ and again for $[m/H] \approx -1.6$, but a dispersion of up to 4 Gyr for the $[m/H] \approx -1.3$ group (which includes the second-parameter pairs). These results imply that (*a*) the duration of halo formation was at least 3 Gyr, and (*b*) age is the primary "second parameter" of HB morphology (see Lee et al 1993, but also the discussion by VandenBerg et al).

Correlations of cluster ages to other parameters From their study of 22 globular clusters, VandenBerg et al have suggested that there is no age gradient from $0 \leqslant R \leqslant 20$ kpc. But SZ showed the outer ($R > 12$ kpc) globular clusters to have a significant second-parameter effect. If age is the dominant second parameter, then the VandenBerg et al results would appear to be in some conflict with SZ for $12 \leqslant R \leqslant 20$ kpc. A resolution may lie in the proposal by Zinn (1993) that the halo globular clusters consist of two subsystems with overlapping spatial distributions. These subsystems are separable by HB morphology: clusters with the bluest HB at any given [Fe/H] define the "old halo" clusters while all others (including clusters shown to be younger by the color-difference method) are considered "young halo" clusters (Figure 5). With this division, Zinn finds a number of correlations: 1. The "old halo" clusters have $\langle V_{rot} \rangle = 70 \pm 22$ km s^{-1} and a line of sight velocity dispersion $\sigma_{los} = 89 \pm 9$ km s^{-1}, while the "young" clusters have $\langle V_{rot} \rangle = -64 \pm 74$ km s^{-1} and $\sigma_{los} = 149 \pm 24$ km s^{-1}. All halo clusters together have $\langle V_{rot} \rangle = 44 \pm 25$ km s^{-1} (Section 3.3.2) and $\sigma_{los} = 113 \pm 12$ km s^{-1}. 2. As a whole, the halo globulars appear to be in a spherical distribution with increased flattening for the inner halo clusters (Hartwick 1987), but the "young" clusters alone are in a spherical distribution, while the "old" clusters, which dominate at smaller R, are in an oblate configuration. 3. While there appears to be no evidence for an abundance gradient for all halo globular clusters with $R > 8$ kpc or $|Z| > 4$ kpc (Armandroff et al 1992), the "old" clusters separately show an ~ 0.50 dex gradient from $R < 6$ kpc to 40 kpc, whereas the "young" clusters show no such gradient. The "old" clusters within $R < 15$ kpc show a correlation of kinematics with abundance.

The Zinn data suggest that the "old" halo globulars were formed during

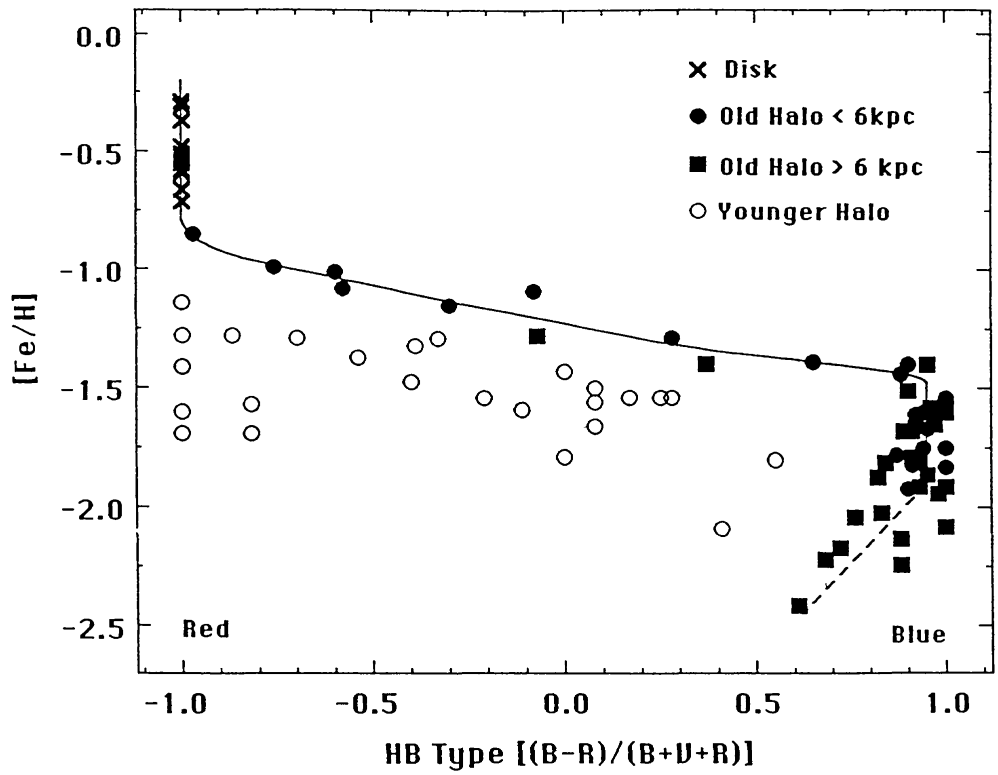

Figure 5 Zinn's (1993) division of the halo globular clusters on the basis of HB type. B is the number of BHB stars, R is the number of RHB stars, and V is the number of RR Lyrae stars. The ridge line is placed through the concentration of "old halo" globulars. The "young halo" globulars are chosen to lie more than 0.4 in HB type to the left of the ridge line at constant [Fe/H]. Disk globulars are defined by [Fe/H] > −0.8. (From Zinn 1993.)

a collapse, while the "young" clusters were formed in one or more fragments which did not participate in this initial collapse, but were accreted at later times, in a manner described in various ways by SZ (1978), Quinn & Goodman (1986), Quinn et al (1992), and others (cf Section 1.2.2). Earlier, Rodgers & Paltoglou (1984) pointed out that the group of globular clusters with $-1.3 \geqslant$ [Fe/H] $\geqslant -1.7$ appeared to be in net retrograde rotation, a fact which they attributed to the accretion of a satellite galaxy. This metallicity range almost exactly matches the range of Zinn's "young" globular clusters (Figure 5). van den Bergh (1993) has confirmed that 8 of the 10 clusters with retrograde orbits fall within this metallicity range, and 5 fall in the tighter range $-1.5 \geqslant$ [Fe/H] $\geqslant -1.6$. The field star equivalent of this accreted satellite galaxy may have been identified by Norris & Ryan (1989a), who noted an excess of retrograde stars in a solar neighborhood sample of dwarfs with [Fe/H] $\leqslant -1.3$.

Halo field stars In light of the discussion in Section 2.1.4, how relevant are globular cluster ages to the bulk of the halo mass in field stars? The blue limit of the most metal-poor subdwarfs is near $B-V = 0.36$, which is similar to the main sequence turnoff of the metal-poor clusters M15 and M92 (Sandage & Kowal 1986, VandenBerg 1990), and implies a similar age. The metal-poor parallax star HD 63077 has been reliably age-dated to be as old as the oldest globular clusters (VandenBerg 1990). This is consistent with the 18.5 ± 3.2 Gyr age found for halo field stars in the *uvbyβ* survey of Nissen & Schuster (1991).

3.2.3 AGE OF IPII The consensus from most studies is that at least some part, and probably the bulk, of IPII is as old as the halo globular clusters. Only one disk globular—47 Tuc—has been included in the cluster dating programs discussed above; an age of $\geqslant 14$ Gyr (modulo future decreases in the isochrone age-scale) is most likely. The disk globulars NGC 6553 (Grenon 1990) and possibly M71 (Hodder et al 1992; but see Heasley & Christian 1991) appear to be as old as 47 Tuc. But note that all of the disk globulars are located within $r_\odot$ and may not represent the IPII locally.

That the IPII field stars are as old as 47 Tuc is suggested from comparison of theoretical isochrones to the apparent turnoff color of intermediate metallicity stars (see Figure 5 of GWK; Carney et al 1989; Rose & Agostinho 1991). Grenon finds an age of 17 Gyr for his IPII defined by $-0.55 \geqslant [m/H] \geqslant -0.90$ (with an uncertainty of $\geqslant 2$ Gyr), but an upper limit of 11–12 Gyr for thin disk stars. From their *uvbyβ* studies, Nissen & Schuster (1991) find their $-1.2 < [Fe/H] < -0.5$ stars, presumably dominated by IPII, to be similarly distributed in age to their 18.5 ± 3.2 Gyr halo sample, but they point out that any IPII AMR or AVR could mask younger IPII stars in their selected sample. If such young stars exist, then, as predicted by Norris & Green (1989), blue ($B-V \leqslant 0.5$) stars with $-0.8 \leqslant [Fe/H] \leqslant -0.4$ should be found in in situ surveys at $1 \leqslant Z \leqslant 5$ kpc. Hardly any such stars have been found (Croswell et al 1991, Majewski 1992a). The Norris & Green prediction was motivated by the suggestion (Norris 1987) that the IPII RHB candidates of Rose (1985) might better be identified with the giant clump typically seen in old open clusters. Identification of these stars as RHB leads to an age like the disk globular clusters, but if they are giants an age 3–6 Gyr smaller is implied. Rose & Agostinho have suggested that the redness of their RHB stars relative to those of 47 Tuc, one of the Norris & Green objections, could be explained if IPII is the same age as 47 Tuc but also several 0.1 dex more metal rich. A second objection to the Rose RHB population is the large number he has found (giving an IPII normalization to the thin disk of 10%, with a scaleheight of 500–1000 pc). In light of the evidence for a more substantial

IPII (Section 3.1), this objection may be weakened, but the discrepancy in the RHB number density among the surveys remains unresolved.

If, as Rodgers (1991) has suggested, RR Lyrae stars do not exist in the thin disk, and the metal-rich RR Lyrae population represents IPII, then its age is $\geqslant 11$ Gyr. This limit derives from comparison to Magellanic Cloud clusters (Olszewski et al 1987): The 10 Gyr old cluster Lindsay 1 has no RR Lyrae stars while NGC 121 (12 Gyr old) does. A new chronometer based on the tidal circularization of binary star orbits has recently been explored by Latham et al (1992). The orbital period at which the transition from elliptical to circular orbits occurs in a coeval population of stars is a function of their age. The transition period is found to be the same for halo and IPII binaries (Carney 1993).

3.3 *Kinematics and Kinematic Gradients*

3.3.1 INTERMEDIATE POPULATION II Measured values of the asymmetric drift have ranged from 20 km s^{-1} (Norris 1987) to 100 km s^{-1} (Wyse & Gilmore 1986) and evoked considerable discussion regarding plausible formation scenarios. On the other hand, complete surveys of stellar proper motions (Murray 1986, Hanson 1989, Spaenhauer 1989, Majewski 1992a) have achieved remarkable agreement that a rather steady Z-gradient of ~ -36 km s^{-1} kpc^{-1} applies to $Z = 7$ kpc (Figure 6); no asymptotic value representing a single IPII V_{rot} is ever reached. Figure 6 presents the IPII asymmetric drifts from selected and tracer studies as a function of sample Z-distances. Lower drift velocities tend to be obtained from IPII samples near the solar neighborhood, while more extreme values tend to be derived from more distant samples. Increasing contamination of more distant samples with slower-rotating halo stars is unlikely to be the primary cause of the apparent correlation since (*a*) the nearby surveys are biased *towards* finding halo stars (selecting by proper motion) whereas the more distant samples are kinematically unbiased, and (*b*) kinematically-biased, local surveys tend to *overestimate* reflex motions (Sections 2.1.2 and 2.3.1). The most likely explanation for the trend is that IPII has an *intrinsic* asymmetric drift gradient.

This concurs with the conclusion of Majewski (1992a) whose in situ Galactic Pole sample shows three concentrations in V velocity which correspond each to the thin disk, IPII, and halo. The mean velocity of the IPII considered separately varies from -24 ± 6 km s^{-1} near 700 pc to -122 ± 26 km s^{-1} at $Z \sim 6$–7 kpc (Figure 6). These data imply a minimum IPII $\langle V_{\mathrm{rot}} \rangle$ near 100 km s^{-1}, but *distinctly separate from the highest estimates of the rotational velocity of the halo*. This $\langle V_{\mathrm{rot}} \rangle$ is precisely where Eggen (1990) has found a discontinuity in the distribution of stars with halo and "old disk" metallicities, and is also near the limit ($\sim$130–

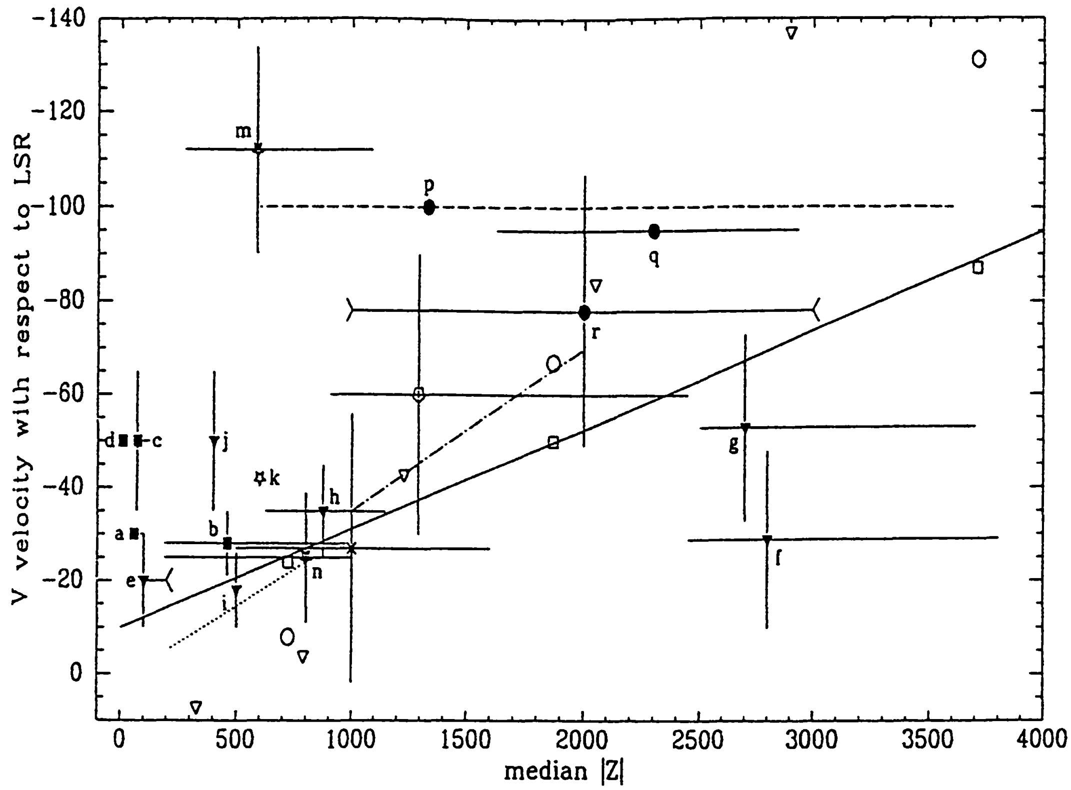

Figure 6 Asymmetric drift measurements of IPII, or reputed tracers thereof, plotted as a function of median $|Z|$ for each sample. Vertical bars indicate the reported error; horizontal bars show the first and third quartiles of the Z-height distribution within each sample when available. Horizontal error bars with arrows instead indicate limits to the $|Z|$ distributions. Drifts from the proper motion selected samples (*solid squares*): a—Sandage & Fouts (1987); b—Carney et al (1989) $-0.35 \leqslant$ [m/H] $\leqslant -0.65$ sample (plotted at the median of $|Z_{\max}|$); c—Casertano et al (1990) reanalysis of previous two samples; d—Nissen & Schuster (1991), $\langle$[Fe/H]$\rangle = -0.4$ sample. Giant star surveys (*solid triangles*): e—Norris (1987) for [Fe/H] ≈ -0.6; f—Ratnatunga & Freeman (1989) for [Fe/H] > -0.7; g—from Morrison et al's (1990) reanalysis of Ratnatunga & Freeman data with $0 >$ [Fe/H] $\geqslant -0.8$; h—Morrison et al (1990) giants $-0.55 \geqslant$ [Fe/H] > -0.78; i—Morrison et al, "enlarged sample," $-1.0 <$ [Fe/H] $\leqslant -0.4$, $Z < 1$ kpc; j—Morrison et al, "enlarged sample," $-1.6 <$ [Fe/H] $\leqslant -1.0$, $Z < 1$ kpc. Analyses of metal-rich RRab Lyrae stars (*stars*): k—Taam et al (1976) $\Delta S \leqslant 2$; m—Strugnell et al (1986) $\Delta S \leqslant 2$, Frenk & White (1980) solution to radial velocities; n—Layden (1993) [Fe/H] > -1, Frenk & White (1980) solution. In situ studies of dwarf stars (*solid circles*): p—Wyse & Gilmore's (1986) reanalysis of Chiu's (1980) data (with the distance distribution for the *entire* sample of stars, not necessarily IPII); q—Wyse & Gilmore (1990; distance distribution estimated); r—A stars from Beers et al (1992). The cross represents Armandroff's (1989) disk globular clusters. The pentagon is Norris' (1986) data for 58 various objects having $-0.6 \geqslant$ [Fe/H] $\geqslant -0.88$ and $Z > 600$ pc. Open squares are for Majewski's NGP data for IPII stars only, with the best fit shown by the solid line. The remaining results plotted are averages of all stars at each Z, without selection for IPII. Open triangles are Spaenhauer's (1989) data, and open squares are Majewski's (1992) data, both at the NGP. The dotted line is an analytic fit to NPM data from Hanson (1989) and the dot-dashed line is a fit to the Murray (1986) SGC data.

140 km s^{-1}) of the "thick disk" clump in the $V_{rot}-$[Fe/H] distribution of Carney et al (1990a; see also Carney et al 1989, Yoshii & Saio 1979, Nissen & Schuster 1991). By the Strömberg asymmetric drift relation (cf equation 12 of GWK), a vertical gradient in σ_U is also to be expected. Spaenhauer (1989) and Majewski (1992a) find σ_U and σ_V gradients when all stars are considered to $Z \approx 4$ kpc, however only for σ_V has this measurement been made for IPII stars alone (a gradient of about 12 km s^{-1} kpc^{-1} is found). Of the various measures of σ_W, there is a correlation of generally higher values (60–70 km s^{-1}) for those surveys with distant samples of IPII stars compared to the measures (35–45 km s^{-1}) from nearby samples (cf Table 1 of Casertano et al 1990). Yoss et al (1987) have also found evidence for a σ_W gradient in their in situ survey, but they point out that some of this may be due to halo contamination.

3.3.2 KINEMATICS OF THE HALO The halo kinematics of Norris (1986) are typical of those measured in the past (cf Freeman 1987, Section 4; GWK, Section 3): $V_{rot} = 37 \pm 10$ km s^{-1} and (σ_r, σ_θ, σ_z = (131, 106, 85)$\pm$(6, 6, 4) km s^{-1}. However, there is considerable disagreement in the measurements between groups, especially considering the rather surprising results from several new surveys that imply a *retrograde* halo rotation (Reid 1990, Allen et al 1991, Majewski 1992a, Schuster et al 1993). Systematic errors (perhaps of the types descibed in Sections 2.1.2, 2.3.1, or 2.4) are always a concern with such unexpected results. On the other hand, the halo globular cluster system contains kinematic subsystems (Section 3.2.2): Rotational velocities measured for the entire halo globular cluster system have been in the range 40–60$\pm$25 km s^{-1} (Woltjer 1975, Hartwick & Sargent 1978, Frenk & White 1980, Zinn 1985, Norris 1986), but these earlier values represent an averaging of the "old" clusters with $\langle V_{rot} \rangle = +70 \pm 22$ km s^{-1} and the "young" clusters with $\langle V_{rot} \rangle = -64 \pm 74$ km s^{-1}. Might the halo field stars be similarly complex?

Most of the halo tracer surveys have given $0 \lesssim \langle V_{rot} \rangle \lesssim 50$ km s^{-1}, as have most of the selected surveys (summaries are given in Strugnell et al 1986, Carney & Latham 1986, Ryan & Norris 1991, and Majewski 1992a). However, almost all of these surveys have been limited to $Z < 2$–3 kpc where IPII clearly dominates (Figure 3). Moreover, the IPII contains stars at least as metal poor as [Fe/H] $= -1.6$ (Section 3.4.2). Thus in order to obtain relatively pure halo samples, one must either probe farther than at least $Z \sim 5$ kpc, or else impose a very conservative metallicity limit of at least [Fe/H] $\leqslant -1.6$ and probably lower. Somewhat different kinematic results tend to be found when these criteria are followed (Majewski 1992b). Ratnatunga & Freeman's (1989) 14 K giants in the direction $(l, b) = (272°, 38°)$ and at $\langle Z \rangle = 12.8$ kpc give an upper limit (since only radial velocities are known) of $\langle V_{rot} \rangle \leqslant +7 \pm 32$ km s^{-1}. The Reid (1990) NGP survey yields $\langle V_{rot} \rangle = -20 \pm 30$ km s^{-1} for ~200 dwarf stars at a mean distance of $\langle Z \rangle \approx 13$ kpc, while Majewski's (1992a) NGP sample of over 100 halo stars, mostly at $Z > 5$ kpc gives $\langle V_{rot} \rangle = -47 \pm 9$ km s^{-1}. Allen et al (1991) found a significant feature in the Z_{max} distribution of angular momentum for the [Fe/H] < -2.0 stars in Schuster & Nissen (1988); the inferred $\langle V_{rot} \rangle$ for stars closer than $Z_{max} = 4$ kpc is near 50 km s^{-1}, but those more distant have $\langle V_{rot} \rangle \sim -87$ km s^{-1}. Schuster et al (1993) reanalyzed the same data: A metal-poor selection alone yielded $\langle V_{rot} \rangle = 22 \pm 9$ km s^{-1}, but isolating high Z_{max} stars by $|W| > 60$ km s^{-1} lowered the velocity to -12 ± 16 km s^{-1}. While $Z_{max} \gtrsim 6$ kpc stars in the local Carney et al (1990a) survey give only marginally negative $\langle V_{rot} \rangle$, their nineteen $Z_{max} > 20$ kpc stars give $\langle V_{rot} \rangle = -27 \pm 23$ km s^{-1}. The [Fe/H] $\leqslant -1.8$ stars in the local surveys by Norris & Ryan (1989b) and Ryan & Norris (1991) yield $\langle V_{rot} \rangle = -22 \pm 6$ km s^{-1} and -20 km s^{-1}, respectively, but must be corrected (by about $+18$ km s^{-1}) for the bias against lower velocity stars (Section 2.1.1); their nonrotating result agrees with the unbiased $\langle V_{rot} \rangle$ they obtain from radial velocities alone. Similar corrections must also be applied to the Carney et al and Schuster et al data.

In summary, 1. tracer surveys of presumed halo stars within several kiloparsecs tend to derive $\langle V_{rot} \rangle \sim 30$ km s^{-1}, but likely have some contamination by metal weak IPII stars without severe metallicity selection criteria[9]; 2. selected surveys from the solar neighborhood, when corrected for kinematic bias, yield nonrotating or slightly prograde velocities; and 3. studies of stars with large Z or Z_{max} find significantly retrograde velocities. To explain the discrepency between groups 2 and 3, either (*a*) there exists a vertical gradient in halo rotation, (*b*) the Reid, Majewski, and Allen et al (and Carney et al, at least for $Z_{max} > 20$ kpc), higher halo samples all have kinematics that are overestimated, or (*c*) the solar neighborhood samples, even with the application of extreme metallicity criteria ([Fe/H] $\leqslant -1.8$), are still contaminated by stars from another, significantly prograde population. The fact that the local surveys of Schuster et al and Carney et al give (corrected) $\langle V_{rot} \rangle \gtrsim 0$ when stars are isolated by metallicity, but retrograde values when stars are isolated by sufficiently high Z_{max} criteria favors either explanation (*a*) or (*c*). Since no proposed formation model can account for a single stellar population with a kinematic gradient that switches the sign of its angular momentum vector, we

[9] Note especially the survey of Morrison et al (1990). They separated out "metal-weak thick disk" stars with [Fe/H] $\geqslant -1.6$, and derived a halo rotational velocity of 17 ± 24 km s^{-1} for their sample of giants and 25 ± 15 km s^{-1} for the Norris (1986) sample.

are led once again to the notion that there may be two metal-poor populations being mixed at low Z. The proposed second population would be flattened[10] and have an [Fe/H] distribution that significantly overlaps that of the traditional metal-poor halo, in order that the total "halo" abundance distribution exhibit no metallicity gradient as a function of V_{rot} (as has been firmly established for metal-poor stars; see Figure 4 of GWK), and only a minor Z-gradient at low Z (Section 3.4). In short, the discrepant field star data can be explained by a halo constructed in analogy with the Zinn (1993) globular clusters. The contrived "second component" may well be the flattened, metal-poor "halo" component which Sommer-Larsen & Zhen (1990) have postulated to contribute 40% of the metal-poor density near the Sun. On the other hand, economy of hypothesis would attribute the flattened, very metal-poor, prograde-rotating population to an already recognized Galactic component—a very metal-poor tail to IPII. Ryan & Norris (1991) were led to similar speculation of a disk with very metal-weak stars as one possible explanation for their finding a correlation between abundance and vertical velocity dispersion down to their most metal-poor stars ([Fe/H] ≈ -3).

3.4 *Abundance Gradients*

3.4.1 THE HALO Evidence for the lack of a halo metallicity gradient has been obtained from surveys of RR Lyraes (Butler et al 1979, Saha 1985, Suntzeff et al 1991), giants (Ratnatunga & Freeman 1989), and dwarf stars (Croswell et al 1991, Majewski 1992a). No gradient was found in earlier studies of halo globular clusters (SZ, Zinn 1985), but the situation is now more complicated since Zinn's "old" halo clusters do exhibit a gradient—$\sim$0.50 dex from $R < 6$ kpc to 40 kpc. Sandage & Fouts (1987) and Ryan & Norris (1991) have found distinct correlations between [Fe/H] and σ_W for halo stars which might also be construed as a correlation of [Fe/H] to Z_{max}. But Carney et al (1990a) explored the [Fe/H]-Z_{max} parameter space directly and claimed only a marginal gradient with Z_{max}. How can these apparently conflicting claims be reconciled? As discussed by Carney et al and Allen et al (1991), the orbits of high velocity stars are often quite chaotic so that W may not uniquely map to Z_{max}. In fact, Carney et al have shown that a Z_{max}-W correlation only exists 1. for those stars with relatively small U, $|W| \lesssim 80$ km s^{-1}, and $|Z_{max}| < 3$ kpc, or 2. to ($|W|$,

[10] It is possible that it is highly flattened in order to account for the Allen et al discontinuity at 4 kpc. Majewski (1992a) has additionally claimed that his measured mean halo reflex velocity is constant above this distance, but both of these findings are in apparent contradiction with the Carney et al data which do not change to a more negative rotational velocity until $Z_{max} \sim 20$ kpc.

Z_{max}) $\approx$ (160 km s^{-1}, 8 kpc) if only stars which avoid the bulge are considered. Thus, the [Fe/H]-σ_W correlations can only imply a vertical abundance gradient for $|Z| < 8$ kpc, with the strongest effect for $|Z| \leqslant 3$ kpc. Note that the Carney et al data show a halo gradient only for $|Z| \leqslant 3$ kpc, while the Saha, Ratnatunga & Freeman, and Majewski samples—which find no gradients—are mostly beyond this distance. The lack of gradient in the Suntzeff et al (1991) data applies only beyond $|Z| \approx 3$ kpc; they too find a small gradient for closer stars. Evidently, all of the claims can be satisfied if a vertical abundance gradient exists that is strongly concentrated to the Galactic plane.

The strong σ_W-[Fe/H] correlation of Sandage & Fouts is for a sample defined by $V < -100$ km s^{-1}, a limit which, when applied to the Carney et al sample, yields a gradient from $\langle$[Fe/H]$\rangle \approx -1.7$ at $Z = 3$ kpc to ~ -1.45 for $Z = 0$. But this gradient is diminished for a limit of $V < -150$ km s^{-1}. From these data, it may be deduced that there exists a population of stars in a flattened distribution for which [Fe/H] $\geqslant -1.45$ but $70 \leqslant V_{rot} \leqslant 120$ km s^{-1}. Part or all of this population may represent stars in the kinematic tail of IPII. Ryan & Norris have also found that as [Fe/H] decreases to -3 dex, σ_W continues to increase even as σ_U, σ_V, and V_{rot} remain constant. Such behavior is difficult to understand dynamically within the context of a single population. It may be that some orbital redistribution mechanism along the lines of those described by Binney & May (1986) or Schuster et al (1992) is at work. But Ryan & Norris point out a more likely solution: the contamination of the traditional, high σ_W halo by another component with substantially metal-poor stars, but having low-σ_W. In order for this scenario to work, either (*a*) this second, low-σ_W component has an identical V_{rot} to the primary halo component in order to maintain the observed constancy of V_{rot} for all [Fe/H] < -1.5, or (*b*) the net $\langle V_{rot} \rangle \approx$ 30–40 km s^{-1} deduced from local halo stars represents an averaging of a slower rotating, high-σ_W component with a faster rotating, low-σ_W component. The latter might be a metal-poor counterpart to the $70 \leqslant V_{rot} \leqslant 120$ km s^{-1} component above, but only at the expense of presuming that the real halo locally is rotating more slowly than 30–40 km s^{-1}; this, however, would reduce the V_{rot} disagreement (Section 3.3.2) between local and distant surveys.

3.4.2 INTERMEDIATE POPULATION II Mean metallicities measured for the IPII have generally been in the range $-0.4 \geqslant$ [Fe/H] $\geqslant -0.6$ (Gilmore & Wyse 1985, Friel 1987, Sandage & Fouts 1987, Yoss et al 1987, Carney et al 1989, Ratnatunga & Freeman 1989, Rose & Agostinho 1991, Schuster et al 1993). On the other hand, it is now evident (Norris et al 1985, Norris 1986, Morrison et al 1990, Majewski 1992a, Morrison 1993) that IPII stars exist to at least -1.6 dex, and probably more metal poor (Sommer-Larsen & Beers 1993). It is not clear whether 1. these metal weak stars represent an asymmetric tail about a mean [Fe/H] near -0.5 dex, 2. $\langle$[Fe/H]$\rangle$ has been overestimated because substantial numbers of metal-poor IPII stars were previously unrecognized, or 3. there exists an IPII metallicity gradient that obfuscates the issue. Sandage & Fouts (1987) have concluded that such a gradient does indeed exist on the basis of a $|W|$-[Fe/H] relationship seen in a kinematically-isolated subsample of IPII stars. Norris (1987) has also found a σ_W-[Fe/H] relationship. But for their stars with [Fe/H] $\leqslant -0.5$ (which should exclude most thin disk stars) at the NGP, Hartkopf & Yoss (1982) found *no* metallicity gradient to $Z \approx 6$ kpc, even though this sample probably represents a mix of both halo and IPII stars. With a larger data set and a narrower metallicity range more representative of IPII, $-0.45 \geqslant$ [Fe/H] $\geqslant -1.00$, Yoss et al (1987) again found no vertical gradient (but see Morrison 1993). Carney et al (1989) found no IPII metallicity variation with $Z_{\rm max}$. Majewski (1992a) has claimed that at most the IPII gradient is -0.05 dex kpc^{-1} based on a photometric abundance study at the NGP. Reid & Majewski (1993) have found that their starcount model better matches these data as well as the Gilmore & Reid (1983) data when a slight (-0.10 dex kpc^{-1}) or no gradient is used for IPII, but the earlier starcount work of Yoshii et al (1987) obtained substantially better fits to their NGP data with an IPII gradient of -0.10 dex kpc^{-1} than with no gradient. Armandroff (1989) has shown that the disk globular clusters to have a modest metallicity gradient with Z, but inclusion of the newly-recognized, [Fe/H] $\leqslant -1.0$ disk clusters M28, M107, and possibly M4 (Section 2.1.3) weakens this gradient (but see Section 4.2). Finally, Morrison (1993) has found a 2 kpc scaleheight for $-1.0 \geqslant$ [Fe/H] $\geqslant -1.6$ "metal weak thick disk" giants at $4 \leqslant r \leqslant 7$ kpc. Depending on the extent to which this population has a density dependence on r, a vertical metallicity gradient at $r_\odot$ may be implied, but only if metal-rich IPII stars have a smaller scaleheight. This latter assumption is now open to more uncertainty (Section 3.1).

3.4.3 ELEMENT RATIOS AS GALACTIC CLOCKS The present uncertainty of the IPII metallicity gradient would seem to be a discouraging limitation to discriminating between evolutionary models. However, there now exists a preponderance of evidence that [Fe/H] is at best poorly correlated with age, which calls into question the usefulness of metallicity gradients as key observables. Geisler (1987) has shown that there is no unique AMR for the open cluster population. Marsakov et al (1990) have shown that it is more appropriate to adopt a "two-dimensional" AMR based on the very large spread of metallicities found for the oldest disk stars (essentially spanning the entire metallicity range of the thin disk) and only a slow narrowing of this range with time. The mean thin disk metallicity has increased but 0.1–0.2 dex over most of its age (cf Carlberg et al 1985). The evolution of the halo and IPII—each which span a large metallicity range in spite of their each having formed over at most a few gigayears—may well have been dominated by processes locally concentrated to individually-evolving, self-enriching gas fragments, perhaps proto-globular clusters (Fall & Rees 1985, Brown et al 1991).

Additional information on the chemical evolution of the Galaxy may be obtained by detailed comparison of element ratios in stars of different populations (see reviews by Wheeler et al 1989, Barbuy 1992, and Pagel 1992). Matteuci & Tornambé (1985), Truran & Thielemann (1987), Wyse & Gilmore (1988; see also GWK) and others have argued that (*a*) the apparent constancy of [O/Fe] for low [Fe/H] stars is due to the enrichment of the ISM solely by Type II supernovae, and (*b*) the appearance of a break towards solar [O/Fe] at intermediate [Fe/H] is a signature of the introduction of additional iron yield from Type Ia supernovae. Based on the theoretical lifetime for the development of significant numbers of Type Ia supernovae,[11] and the appearance of a break at [Fe/H] ≈ -1.0, they deduced that the timescale at which the Galaxy had enriched to [Fe/H] ≈ -1.0 was relatively short—less than 1 Gyr. But this interpretation of the Galactic enrichment history is now less obvious. As discussed in Section 3.2.2, the position of the [O/Fe] break has recently been claimed to be as low as [Fe/H] ≈ -1.7, and possibly nonexistent altogether (Abia & Rebolo 1989). Moreover, as Carney et al (1990a) point out, even accepting the basic premise of the proposed enrichment scenario and the timescales derived therefrom does not imply a short duration for the formation of the entire halo per se if it was constructed via the agglomeration of multiple fragments, each with its own star formation history. GWK have acknowledged that the significant scatter in the relative abundances of *r*- and *s*-process elements in metal-poor stars may be a manifestation of the inhomogeneity of the nascent halo, though they counter the fragment idea by stressing an apparently small scatter in the [O/Fe] to [Fe/H] distribution (see also Wyse & Gilmore 1993). But at present, the evidence appears weighted towards an early Galaxy with a very complex, inhomogeneous distribution of metals.

3.5 *Evidence for Accretion in the Galaxy*

The idea that some part of the halo may have been accreted in the form of dwarf galaxies is suggested by the retrograde rotation of the "young"

[11] This is driven mainly by the main sequence lifetime of the expected largest contributors of appropriate Type Ia supernova binary precursors, $\sim 5\ M_{\odot}$ stars.

globular clusters (Section 3.2), while there is some evidence, albeit controversial, that the halo field population may also be in net retrograde rotation (Section 3.3.2). Recall (Section 1.3) that consideration of simple dynamical friction arguments suggests that the Milky Way should have accreted about the equivalent of one LMC mass in a Hubble time. This immediately calls to mind the present interaction between the Magellanic Cloud system and the Milky Way as a paradigm for such accretion. Reviews of the Cloud-Galaxy interaction may be found in Mathewson (1985), Irwin (1991), Wayte (1991), and Majewski (1993b). The existence of the Magellanic Stream, a swath of HI gas extending from the Clouds and over 180° of the sky in a trailing orbit (Jones et al 1989, Tucholke & Hiesgen 1991), is strong evidence that the Clouds are being disrupted and merged with the Galaxy.

Tantalizing circumstantial evidence that at least one other large Galactic satellite may have once existed is found in the distribution of the present population of dwarf spheroidal galaxies. Lynden-Bell (1982; see also Kunkel & Demers 1976) pointed out the remarkable circumstance that the Galactic satellites all appear to be situated along two close, great circles ("streams") in the sky, each of which contain the Galactic poles, and one of which contains the Magellanic Stream. The more recently discovered Galactic satellites—Sextans and Phoenix—also follow this alignment. Moreover, Kunkel (1979) demonstrated that the radial velocity distribution of the dwarf spheroidals are consistent with their motions being orbital along the alignment, rather than randomly directed. Based on this evidence, Lynden-Bell proposed that Ursa Minor, Draco, and Carina were once part of a greater Magellanic Galaxy, and suggested that the dwarfs in the other "great stream"—Fornax, Sculptor, Leo I and II—are the remnants of another, former greater satellite which is now either totally disrupted or diminished to one of the present dwarfs (perhaps Fornax, which alone among the dwarfs has its own globular cluster system). An alternative explanation of the dwarf spheroidal system may have to do with the stability of polar orbits whereby, of an inchoate population of dwarfs randomly situated in phase space, those surviving to the present were initially on favored orbits; but of course this scenario also depends on accretion of satellites—those born on fatal orbits.

If some halo field stars were derived from accretion of satellites, we might expect to find evidence of these former entities as clumping in stellar phase space, since disrupted debris should retain memory of the parent angular momentum for some time. The existence of moving groups of halo stars has been long debated. While candidate groups continue to be reported (Eggen 1987, Sommer-Larsen & Christensen 1987, Doinidas & Beers 1989, Croswell et al 1991, Arnold & Gilmore 1992, Majewski

1992a, Poveda et al 1992; see Section 5 of Freeman 1987 for earlier references), conclusive verification of their authenticity has proven difficult. Moreover, globular cluster destruction (Section 2.1.3) is also expected to generate moving groups, so this is not necessarily the best avenue of proof for the accretion of large satellites.

4. THE FORMATION MODELS REVISITED

4.1 *Review of Key Observables and Assessment of the Models*

This section is a summary appraisal of the data relating to the "key observables" outlined in Section 1. It represents no more than a scorecard of the most persuasive evidence at present, and dissenting opinion exists on almost every point. The following list enumerates the eight principal Galactic properties discussed in Section 3:

1. The Galactic halo and IPII appear to be coeval and ancient (Sections 3.2.2 and 3.2.3).
2. The halo globular clusters formed over several Gyr (Section 3.2.2).
3. The majority of evidence supports the idea that the old thin disk is discrete in age from the IPII and halo components by several Gyr (Section 3.2).
4. The halo and IPII have disjoint kinematical distributions, based on the separation of the rotational velocities measured for each (Section 3.3).
5. The IPII probably has a kinematical gradient, consistent with a dissipative origin, but of such extent as to exclude stochastic heating as a potential formation mechanism (Section 3.3.1).
6. The halo lacks a metallicity gradient, at least for that part which is more that several kiloparsecs from the Galactic plane (Section 3.4.1).
7. The IPII most likely has a relatively mild (0 to -0.1 dex kpc^{-1}) metallicity gradient (Section 3.4.2). It possesses a remarkable metallicity spread, reaching to [Fe/H] $\leqslant -1.6$.
8. There is a great deal of circumstantial evidence suggesting that at least part of the halo has been accreted (Sections 3.2.2 and 3.5).

The evidence that prompted the SZ suggestion that the formation of the halo may have been more chaotic than the rapid and homogeneous collapse of ELS was the lack of a metallicity gradient and the prominence of the second-parameter effect in the outer halo globular clusters. The lack of an abundance gradient in the (nonlocal) halo now seems well established (point 6). That the conspicuousness of the second-parameter effect in the outer halo is related to a significant age range appears to be substantiated by the great advances made in relative globular cluster age dating. Point 8 provides additional support to the notion that the formation of the halo may have been dominated by processes which, according to SZ, are related to "transient protogalactic fragments that continued to fall into dynamical equilibrium with the Galaxy for some time after the collapse of its central regions had been completed."

Points 1, 3, 4, and 5 have the greatest weight in assessing the models in Table 1. Uncertainty regarding an IPII metallicity gradient (point 7) means that this "key observable" cannot presently be used to constrain models. However, the existence of substantially metal-weak IPII stars could be a problem for Model 3. Very little is known about the kinematic and chemical discreteness of the thin disk from IPII. The fact that they do appear to be discrete in age would seem to favor Models 6–8. On the other hand, incorporating into Models 1–4 a star formation history dominated by bursts (Section 4.2), as is the case within the thin disk (Figure 4), could reconcile the age gap with dissipational formation models if the formation of IPII represents just one burst phase in a punctuated, active/quiescent cycle of disk formation. The dissipational models are strongly favored by point 5; whereas Model 6 seems incapable of producing the large asymmetric drifts implied at large Z, Model 8 is unable to account for the small asymmetric drifts at small Z. Model 5 also predicts an IPII asymmetric drift gradient, but (Section 1.2.2) secular diffusion cannot account for the large σ_W observed in the old thin disk, let alone in IPII. Moreover, Model 5 has difficulty accounting for a thin disk/IPII age gap.

Perhaps the most critical of the summary points are those relating to the halo/IPII interface. The apparent discontinuity between the rotational velocities of the two populations is hard to account for if IPII was formed during a more or less smooth transition to a dissipational structure (Model 1), or if IPII is simply a flattened subset of halo stars (Model 8). The apparent coevality of the two components strongly disfavors scenarios where the formation of the halo precedes that of IPII (Models 1–3). Together, points 1 and 4 suggest that the halo and IPII formed at the same time but through fairly unrelated processes—the essence of Model 4.

On the basis of a tally of both theoretical objections (Section 1.2.2) and the key observables, the most favored scenario in Table 1, and the only one consistent with all of the relevant information, is Model 4. But note, this model is also the least well defined mainly because its crux (as presented here, but not necessarily in the various cited references) is defining the relationship, or rather the lack thereof, between the halo and IPII rather than detailing specifically *how* IPII formed. Either a top-down or bottom-up scenario might apply, *but without the halo playing an essential role in IPII formation*. Since the main objections to the dissipational models of IPII formation have to do with the coevality with and discreteness from the halo, whereas the various bottom-up pictures face other shortcomings, isolating the halo from the sequence of disk formation events would bring the dissipational IPII models back into favor. Thus, some combination of dissipational collapse (modified Models 1 and 2) and Model 4 appears to be a useful point of departure from which to construct a scenario for the formation of the Galaxy.

4.2 *A Scenario for the Formation of the Galaxy*

Here a specific scenario is proposed for the formation of the Galaxy that takes into account the points in Section 4.1. Not unexpectedly, the proposed model is a hybrid of many of those presented in Section 1, and borrows those features most consistent with the data. It has also been heavily influenced by the following additional observations:

9. The IPII is a significant Galactic component which dominates from $Z \approx 1$ kpc to at least $Z = 3$–5 kpc and perhaps farther. It contributes 20% of the total stellar density to at least 5 kpc and perhaps to more than 8 kpc (Section 3.1, Figure 3).
10. The SFR history of at least one structure in the Galaxy, the thin disk, was not smooth, but rather, punctuated by star formation bursts up to several gigayears in duration, and separated by lulls of at least 1–3 Gyr in duration (Section 3.2.1, Figure 4).
11. A division of the halo globular clusters based on HB morphology suggests that "young" clusters may have been accreted, based on the lack of a metallicity gradient and retrograde rotation. The "old" halo globulars show a metallicity gradient, a rotational velocity of 70 km s^{-1}, and an oblate spatial distribution (Section 3.2.2).
12. In addition to the "old" halo globular cluster system, there have been various other claims for flattened halo stellar populations near to the Galactic plane (Section 3.1).
13. The existence of a flattened, large asymmetric drift ($70 \leqslant V_{\rm rot} \leqslant 120$ km s^{-1}) population of stars more metal-rich ([Fe/H] $\geqslant -1.45$) than the typical halo could account for the apparent "halo" metallicity gradient for $Z \lesssim 3$ kpc (Section 3.4.1). A similarly rotating, flattened, but very metal-poor counterpart would resolve the discrepant halo rotational velocities between local selected surveys and distant in situ surveys (Section 3.3.2).
14. The AMR of the disk is "two-dimensional," with a large amount of scatter at most ages (Sections 3.2.1 and 3.4.3). Metallicity is not a good indicator of age (Section 3.4.3).

In analogy with what is suggested by the halo globular cluster system, and according to the tenets of Model 4, it is proposed that the formation of the Galaxy proceeded along two separate courses. The bulk of the protogalactic gas participated in a central collapse, which eventually became the disk. Some gas in the outer halo was left behind as independently evolving, self-enriching, SZ fragments. Apart from perhaps some enrichment "cross-talk" through supernova ejecta, these fragments probably had little to do with the early evolution of the main gas distribution which was contracting and spinning up to become the Galaxy. The outer fragments possibly formed orbiting Magellanic-type galaxies, some of which were accreted at later times, leaving behind a detritus of field stars, globular clusters, and perhaps the dwarf spheroidals (cf Section 3.5). The substructure in the globular cluster system discovered by Rodgers & Paltoglou (1984), Zinn (1993), and van den Bergh (1993) is a hallmark of this dual evolution. The "young" halo globulars are the likely remnants of accreted dwarf galaxies. An example of this process today is the destruction of the Magellanic system which is creating the Magellanic Stream, may have left behind the globular clusters Pal 12 and Ruprecht 106 (Section 3.2.2), and may even have given birth to the dwarf spheroidals Ursa Minor, Draco, and Carina (Section 3.5). The apparent net retrograde rotation for the "young" halo globulars may reflect a random imbalance in the original orbital distribution of a small number of fragments, or it may be related to the dynamics of decaying bodies: Numerical models (Keenan & Innanen 1975, Quinn & Goodman 1986) show that retrograde satellites are more robust to tidal decay, while prograde satellites have short lifetimes before they rapidly sink into the central mass. On the other hand, the "old halo" and the disk globular cluster systems each have significant rotation, exhibit internal metallicity gradients, and make up spatially-flattened distributions. It may be constructive to think of them as parts of one dissipative, structural entity. Indeed, new orbital data (Section 2.1.3) indicate some fuzziness in the disk/halo cluster distinction. As one entity, the "old halo" + disk cluster system exhibits significant "spin-up," from $V_{\rm rot} \sim 70$ km s^{-1} for the "old halo" globulars to 195 km s^{-1} for the disk globulars. The ~ 14 Gyr ages for 47 Tuc and NGC 6553 (Section 3.2.2) are consistent with the notion that the disk and "old halo" systems are the products of a single, early dissipational collapse.

What are the field star populations associated with the two formation processes? A strong case can now be made that IPII represents the first coherent structure formed in the general collapse of the Milky Way, and that it is the product of dissipation. In the parlance of previous authors, what is being referred to here are the "thick disk," the "extended disk," the "inner spheroid," the "flattened halo," the "metal-weak thick disk," the "high velocity stars," and "intermediate Population II," terms that I propose are referring to the same, or parts of the same, entity. Accordingly, the entire dissipative "old halo" + disk globular system is to be identified with *IPII* and *not* to the extreme halo subdwarfs, which are proposed to be the field star equivalent of the "young" globular clusters. The strength of the suggested association between the "old halo"+disk globulars and IPII comes from the great similarity in age (point 1), kinematics, and metallicity. The range of mean rotational velocities encompassed in the kinematical gradient of the "old halo"+disk globular cluster system, $70 \leqslant V_{rot} \leqslant 195$ km s^{-1}, is nearly identical to that encompassed in the gradient of the IPII field stars, which appears to reach as low as $V_{rot} = 100$ km s^{-1} (Figure 6). Point 13 suggests that IPII stars with rotational velocities from 70 to 100 km s^{-1} may even exist. The remarkable metallicity range of IPII is also very compelling. With IPII stars verified to at least [Fe/H] $= -1.6$, and suspected at even lower metallicities (Section 3.4.2), the entire range of globular cluster metallicities, $-0.2 \geqslant$ [Fe/H] $\geqslant -2.3$ may well be encompassed by IPII field stars. The very metal-weak, flattened component of Sommer-Larsen & Zhen (1990; see also Sommer-Larsen & Beers 1993) may represent this most extreme tail of IPII. Such a ubiquitous IPII, with very broad metallicity, kinematical, and spatial distributions, would greatly simplify Galactic structure by stemming the proliferation of Galactic components introduced to explain each observational peculiarity; the many flattened "halo" structures that have been reported (Section 3.1) or postulated (point 13) can be accommodated as subpopulations of IPII.

As demonstrated for the thin disk (Figure 4), the evolution of the Galaxy has been characterized by bursts of star formation. The main structure of the stellar thin disk has probably been constructed in 3 (or more?) major burst periods (A, B, C, . . .) each up to several giga-years in length and separated by lulls of at least 1–3 Gyr duration. The age range of IPII and the "old halo"+disk globulars is also several gigayears, and, although still unsettled due to uncertainties in age scales, the age gap between the thin and IPII disks also seems to be around several gigayears. The similarity of these star formation duty cycles suggests a continuous pattern tied to the dissipative formation of the Galactic disk, something along the lines of the models by Larson (1974), Marsakov & Suchkov (1977), Berman & Suchkov (1991), Burkert et al (1992), and Katz (1992). In analogy to the three bursts (A–C) seen in Barry's (1988) data, the IPII may represent the first active phase of disk star formation (burst D?) more than 14 Gyr ago. At the beginning of this phase, say ~ 17 Gyr ago, the primordial gas cloud had contracted to a flattened structure and spun up to $V_{rot} \approx 70$ km s^{-1} at a radius corresponding to the present $r_{\odot}$. This initial concentration of gas was very clumpy and, with little opportunity for large-scale mixing of enriched gas, gave rise to a puffed up stellar disk with a wide metallicity spread. The dimensions of this first disk are traced by the present spatial extent (Section 3.1) of IPII. As in the original ELS scenario, stars formed at this time retained the velocity characteristics of the parent gas which, however, was in a dissipational collapse rather than freefall. During the several gigayear-long burst of star formation, there is ELS spin-up, giving rise to the observed IPII kinematic gradient (Section 3.3.1). The need for a concomitant metallicity gradient in this population is diminished if it is acknowledged that the gas in this star formation burst was very inhomogeneous, with scattered, disconnected sites of star formation and self-enrichment in the regions of highest gas density, and, moreover, if exchange and mixing of enriched gas occurred mainly during "hot," interburst phases.

After several gigayears, star formation in the initial burst became suppressed, probably as a result of intense heating from supernovae (Marsakov & Suchkov 1977), which impart energy, momentum, and metal-enriched ejecta into the remaining gas (Section 1.2). During this several gigayear delay, the hot, metal-enriched gas was able to mix, so that the next population of stars had both a higher mean metallicity and a smaller metallicity range. Eventually, the gas recontracted and cooled out of the hot, expanded phase and initiated a new burst of star formation, possibly burst C, and the alternating cycles of star formation and suppression repeated to form burst B. Eventually the gas managed to settle into the present thin disk which is in the midst of burst A. With each subsequent cycle, the gas became evermore mixed so that the mean stellar metallicity rose and the metallicity spread narrowed. It is not clear whether the hotter kinematics of burst B and C stars compared to burst A are due to initial conditions, or whether the gas which formed each of these bursts had settled to relatively thin layers and the present kinematics of older stars reflect the action of dynamical heating processes (Section 1.2.2). In theory, some stochastic heating must occur in disk stars, but note that the $\sigma_W = 27$ km s^{-1} of Barry's burst C stars is just beyond the apparent theoretical limits of this process. These stars could have been accelerated through violent heating events (but note the mass constraints in Section 1.2.2), perhaps one or more SZ fragments "falling into dynamical equilibrium" with the Galaxy. If there was a single such event it must have occurred about 3 Gyr ago or so in order to have almost uniformly accelerated all stars of ages 3–11 Gyr in the disk; otherwise, there may have been several smaller heating events during the time 3–11 Gyr ago. It is worth noting that bursts A and B each coincide with major star formation episodes thought to have taken place in the LMC (Noh & Scalo 1990).

In this scenario, the IPII is envisaged as the first disk burst ("burst D"?) and is "discrete" from the thin disk (more specifically, the stars in burst C) in the same sense that stars formed in burst B are distinct from stars created in burst A. The main distinction is age, whereas the various burst populations are reckoned to have significant chemical, kinematical, and spatial overlap. On the other hand, what is proposed here to be the true halo—those stars that are the debris of disrupted SZ fragments—is manifestly distinct from the various disk populations on the basis of origin, a distinction most evident kinematically. This description of stellar populations bears similarity to the spirit of discussions in the 1950s—and summarized at the 1957 Vatican Conference (O'Connell 1958)—when distinctions were made between the subdwarfs of "Halo Population II" and the high velocity disk stars of "Intermediate Population II." At that time, the thin disk was further divided into an age sequence: the "weak-line" stars of the "disk population," "older Population I," and the youngest stars of "extreme Population I." Such consideration of distinct disk groups seems ever more appropriate with the understanding that the creation of the disk was a rather discontinuous affair. An example of the insight offered by such an approach may be the recent work of Yoss (1992) which shows that Roman's (1950, 1952) assignment of stars to distinct spectroscopic classes results in far more homogeneous kinematical groups than a division based on [Fe/H] alone. The kinematical and abundance characteristics of Roman's "weak CN," "weak-line," and "strong-line" groups are in remarkable agreement with those displayed by bursts C, B, and A, respectively.[12]

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[12] Yoss ascribes the degraded kinematical homogeneity when stars are divided on the basis of [Fe/H] primarily to the effects of random errors in the abundance determinations. But much of the degradation can be attributed to the large scatter in the disk AMR at all ages. He also identifies the weak CN group with IPII on the basis of its mean asymmetric drift, even though he acknowledges that the vertical velocity dispersion of 23 ± 5 km s^{-1} is significantly lower than traditionally associated with this component. Association instead with the Barry burst C stars, or perhaps a mix of burst C and IPII stars, yields a more consistent match.

Literature Cited

Abia, C., Rebolo, R. 1989. *Ap. J.* 347: 186
Adamson, A. J., Hill, G., Fisher, W., Hilditch, R. W., Sinclair, C. D. 1988. *MNRAS* 230: 273
Aguilar, L., Hut, P., Ostriker, J. P. 1988. *Ap. J.* 335: 720
Allen, C., Schuster, W. J., Poveda, A. 1991. *Astron. Astrophys.* 244: 280
Armandroff, T. E. 1989. *Astron. J.* 97: 375
Armandroff, T. E. 1993. See Brodie & Smith 1993. In press
Armandroff, T. E., Zinn, R. 1988. *Astron. J.* 96: 92
Armandroff, T. E., Da Costa, G. S., Zinn, R. 1992. *Astron. J.* 104: 164
Arnold, R., Gilmore, G. 1992. *MNRAS* 257: 225
Baade, W. 1944. *Ap. J.* 100: 137
Baade, W. 1958. *Specola Vaticana* 5: 303
Bahcall, J. N. 1986. *Annu. Rev. Astron. Astrophys.* 24: 577
Bahcall, J. N., Casertano, S. 1986. *Ap. J.* 308: 347
Bahcall, J. N., Soneira, R. M. 1980. *Ap. J.Suppl.* 44: 73
Bahcall, J. N., Soneira, R. M. 1984. *Ap. J. Suppl.* 55: 67
Barbuy, B. 1992. See Barbuy & Renzini 1992, p. 143.
Barbuy, B., Erdelyi-Mendes, M. 1989. *Astron. Astrophys.* 214: 239
Barbuy, B., Renzini, A., eds. 1992. *The Stellar Populations of Galaxies, IAU Symp. No. 149*. Dordrecht: Kluwer
Barbanis, B., Woltjer, L. 1967. *Ap. J.* 150: 461
Barnes, J., White, S. D. M. 1984. *MNRAS* 211: 753
Barry, D. C. 1988. *Ap. J.* 334: 436
Becker, W. 1950. *Sterne und Sternsysteme*. Dresden, Leipzig: Steinkopf. 2nd ed., p. 166
Beers, T. C., Preston, G. W., Shectman, S. A. 1985. *Astron. J.* 90: 2089
Beers, T. C., Preston, G. W., Shectman, S. A., Doinidas, S. P., Griffin, K. E. 1992. *Astron. J.* 103: 267
Beers, T. C., Preston, G. W., Shectman, S. A., Kage, J. A. 1990. *Astron. J.* 100: 849
Berman, B. G., Suchkov, A. A. 1991. *Astrophys. Space Sci.* 184: 169
Bessell, M. S., Sutherland, R. S., Ruan, K. 1991. *Ap. J. Lett.* 383: L71
Binney, J., Lacey, C. 1988. *MNRAS* 230: 597
Binney, J., May, A. 1986. *MNRAS* 218: 743
Binney, J., Tremaine, S. 1987. *Galactic Dynamics*. Princeton: Princeton Univ. Press
Blaauw, A., Schmidt, M., eds. 1965. *Galactic Structure: Stars & Stellar Systems, Vol. 5*. Chicago: Univ. Chicago Press
Bolte, M. 1989. *Astron. J.* 97: 1688
Bolte, M. 1990. *J. R. Astron. Soc. Can.* 84: 137
Bolte, M. 1993. See Majewski 1993a, p. 173
Bond, H. E. 1970. *Ap. J. Suppl.* 22: 117
Bond, H. E., 1980. *Ap. J. Suppl.* 44: 517
Brodie, J., Smith, G., eds. 1993. *The Globular Cluster-Galaxy Connection*. ASP Conf. Ser. San Francisco: Astron. Soc. Pac. In press
Brosche, P., Tucholke, H.-J., Klemola, A. R., Ninkovic, S., Geffert, M., Doerenkamp, P. 1991. *Astron. J.* 102: 2022
Brown, J. A., Sneden, C., Lambert, D. L., Dutchover, E. 1989. *Ap. J. Suppl.* 71: 293
Brown, J. H., Burkert, A., Truran, J. W. 1991. *Ap. J.* 376: 115
Buonanno, R., Buscema, G., Fusi Pecci, F., Richer, H. B., Fahlman, G. G. 1990. *Astron. J.* 100: 1811
Buananno, R., Corsi, C. E., Fusi Pecci, F. 1989. *Astron. Astrophys.* 216: 80
Buananno, R., Corsi, C. E., Fusi Pecci, F., Richer, H. B., Fahlman, G. G. 1993. *Astron. J.* 105: 184
Burbidge, E. M., Burbidge, G. R., Fowler, W. A., Hoyle, F. 1957. *Rev. Mod. Phys.* 29: 547
Burkert, A., Truran, J. W., Hensler, G. 1992. *Ap. J.* 391: 651
Burstein, D. 1979. *Ap. J.* 234: 829
Butcher, H. R. 1987. *Nature* 328: 127
Butler, D., Kinman, T. D., Kraft, R. P. 1979. *Astron. J.* 84: 993
Cacciari, C., Clementini, G., Buser, R. 1989. *Astron. Astrophys.* 209: 154
Cameron, L. M. 1985. *Astron. Astrophys.* 152: 250
Canuto, V. M., Mazzitelli, I. 1991. *Ap. J.* 370: 295
Caputo, F., Castellani, V. 1984. *MNRAS* 207: 185
Carbon, D. F., Barbuy, B., Kraft, R. P., Friel, E. D., Suntzeff, N. B. 1987. *Publ. Astron. Soc. Pac.* 99: 335
Carlberg, R. G. 1987. *Ap. J.* 322: 59
Carlberg, R. G., Dawson, P. C., Hsu, T., VandenBerg, D. A. 1985. *Ap. J.* 294: 674
Carlberg, R. G., Sellwood, J. A. 1985. *Ap. J.* 292: 79
Carney, B. W. 1979. *Ap. J.* 233: 211
Carney, B. W. 1983. *Astron. J.* 88: 623
Carney, B. W. 1993. See Majewski 1993a, p. 83
Carney, B. W., Aguilar, L., Latham, D. W., Laird, J. B. 1990a. *Astron. J.* 99: 201
Carney, B. W., Laird, J. B., Latham, D. W., Kurucz, R. L. 1987. *Astron. J.* 94: 1066
Carney, B. W., Latham, D. W. 1986. *Astron. J.* 92: 60
Carney, B. W., Latham, D. W. 1987. *Astron. J.* 93: 116

Carney, B. W., Latham, D. W., Laird, J. B. 1989. *Astron. J.* 97: 423
Carney, B. W., Latham, D. W., Laird, J. B. 1990b. *Astron. J.* 99: 572
Carney, B. W., Storm, J., Jones, R. V. 1992. *Ap. J.* 386: 663
Casertano, S., Ratnatunga, K. U., Bahcall, J. N. 1990. *Ap. J.* 357: 435
Catelan, M. 1992. *Astron. Astrophys.* 261: 457
Chaboyer, B., Sarajedini, A., Demarque, P. 1992. *Ap. J.* 394: 515
Chamberlain, J. W., Aller, L. H. 1951. *Ap. J.* 114: 52
Chernoff, D. L., Shapiro, S. L. 1987. *Ap. J.* 322: 113
Chiu, L-T. G. 1980. *Ap. J. Suppl.* 44: 31
Clayton, D. D. 1988. *MNRAS* 234: 1
Cowan, J. J., Thielemann, F.-K., Truran, J. W. 1987. *Ap. J.* 323: 543
Crawford, D. L. 1975. *Astron. J.* 80: 955
Croswell, K., Latham, D. W., Carney, B. W., Schuster, W., Aguilar, L. 1991. *Astron. J.* 101: 2078
Cudworth, K. M. 1976. *Astron. J.* 81: 519
Cudworth, K. M. 1990. *Astron. J.* 99: 590
Cudworth, K. M., Hanson, R. B. 1993. *Astron. J.* 105: 168
Da Costa, G. S., Armandroff, T. E., Norris, J. E. 1992. *Astron. J.* 104: 154
D'Antona, F., Mazzitelli, I. 1978. *Astron. Astrophys.* 66: 453
Dawson, P. C. 1986. *Ap. J.* 311: 984
Deliyannis, C. P., Demarque, P. 1991. *Ap. J.* 379: 216
Deliyannis, C. P., Demarque, P., Kawaler, S. D. 1990. *Ap. J. Suppl.* 73: 21
Demarque, P. Deliyannis, C. P., Sarajedini, A. 1991a. In *Observational Tests of Cosmological Inflation*, ed. T. Shanks, A. J. Banday, R. S. Ellis, C. S. Frenk, A. W. Wolfendale, p. 111. Dordrecht: Kluwer
Demarque, P., Guenther, D. B., Green, E. M. 1991b. See Janes 1991, p. 259
de Vaucouleurs, G. 1977. *Astron. J.* 82: 456
Doinidis, S. P., Beers, T. C. 1989. *Ap. J. Lett.* 340: L57
Duquennoy, A., Mayor, M., Halbwachs, J.-L. 1991. *Astron. Astrophys. Suppl.* 88: 281
Dyer, E. R. 1954. *Astron. J.* 59: 221
Eggen, O. J. 1979. *Ap. J.* 230: 786
Eggen, O. J. 1982. *Ap. J. Suppl.* 50: 221
Eggen, O. J. 1983. *Ap. J. Suppl.* 51: 183
Eggen, O. J. 1987. See Gilmore & Carswell 1987, p. 211
Eggen, O. J. 1990. *Astron. J.* 100: 1159
Eggen, O. J., Lynden-Bell, D., Sandage, A. R. 1962. *Ap. J.* 136: 748 (ELS)
Fall, S. M., Rees, M. J. 1977. *MNRAS* 181: 37p
Fall, S. M., Rees, M. J. 1985. *Ap. J.* 298: 18
Fernley, J. A. 1993. *Astron. Astrophys.* 268: 591
Fouts, G., Sandage, A. 1986. *Astron. J.* 91: 1189
Fowler, W. A. 1987. *Q. J. R. Astron. Soc.* 28: 87
Fowler, W. A., Meisl, C. C. 1986. In *Cosmogonical Processes*, ed. W. D. Arnett, C. J. Hansen, J. W. Truran, S. Tsuruta, p. 83. Utrecht: VNU
Freeman, K. C. 1980. In *Photometry, Kinematics and Dynamics of Galaxies*, ed. D. S. Evans, p. 85. Austin: Univ. Texas
Freeman, K. C. 1987. *Annu. Rev. Astron. Astrophys.* 25: 603
Freeman, K. C. 1993. See Majewski 1993a, p. 125
Frenk, C. S., White, S. D. M. 1980. *MNRAS* 193: 295
Friel, E. D. 1987. *Astron. J.* 93: 1388
Frogel, J. A. 1988. *Annu. Rev. Astron. Astrophys.* 26: 51
Fuchs, B., Wielen, R. 1987. See Gilmore & Carswell 1987, p. 375
Fusi Pecci, F., Ferraro, F. R., Crocker, D. A., Rood, R. T., Buananno, R. 1990. *Astron. Astrophys.* 238: 95
Geisler, D. 1987. *Astron. J.* 94: 84
Giclas, H. L., Burnham, R., Thomas, N. S. 1968. *Lowell Obs. Bull.* 7: 67 (LPMS)
Gilmore, G. F. 1984. *MNRAS* 207: 223
Gilmore, G., Carswell, B., eds. 1987. *The Galaxy*. Reidel: Dordrecht
Gilmore, G. F., King, I. R., van der Kruit, P. C. 1990. *The Milky Way as a Galaxy*. Mill Valley, Calif: Univ. Sci. Books
Gilmore, G., Reid, N. 1983. *MNRAS* 202: 1025
Gilmore, G., Wyse, R. F. G. 1985. *Astron. J.* 90: 2015
Gilmore, G., Wyse, R. F. G. 1986. *Nature* 322: 806
Gilmore, G., Wyse, R. F. G., Kuijken, K. 1989. *Annu. Rev. Astron. Astrophys.* 27: 555 (GWK)
Gilroy, K. K., Sneden, C., Pilachowski, C. A., Cowan, J. J. 1988. *Ap. J.* 327: 298
Gliese, W. 1986. In *Astrometric Techniques, IAU Symp. No. 109*, ed. H. K. Eichhorn, R. J. Leacock, p. 653. Dordrecht: Reidel
Gliese, W., Jahreiss, H. 1989. *Contrib. Van Vleck Obs.* 8: 3
Gomez, A. E., Delhaye, J., Grenier, S., Jaschek, C. Arenou, F., Jaschek, M. 1990. *Astron. Astrophys.* 236: 95
Gratton, R. G., Ortolani, S. 1988. *Astron. Astrophys. Suppl.* 73: 137
Green, E. M., Morrison, H. L. 1993. See Brodie & Smith 1993. In press
Green, E. M., Norris, J. E. 1990. *Ap. J. Lett.* 353: L17
Grenon, M. 1990. In *Astrophysical Ages and Dating Methods*, ed. É. Vangioni-Flam, M. Cassé, J. Audouze, J. Tran Thanh Van, p. 153. Gif sur Yvette: Ed. Frontières

Griffin, R. F., Gunn, J. E., Zimmerman, B. A., Griffin, R. E. M. 1988. *Astron. J.* 96: 172
Gunn, J. E., Griffin, R. F., Griffin, R. E. M., Zimmerman, B. A. 1988. *Astron. J.* 96: 198
Guo, X., Girard, T. M., van Altena, W. F., López, C. E. 1993. *Astron. J.* Submitted
Hanson, R. B. 1979. *MNRAS* 186: 875
Hanson, R. B. 1980a. In *Star Clusters*, *IAU Symp. No. 85*, ed. J. E. Hesser, p. 71. Dordrecht: Reidel
Hanson, R. B. 1980b. *MNRAS* 192: 347
Hanson, R. B. 1989. *Bull. Am. Astron. Soc.* 21: 1107
Hardorp, J. 1980. *Astron. Astrophys.* 88: 334
Hartkopf, W. I., Yoss, K. M. 1982. *Astron. J.* 87: 1679
Hartwick, F. D. A. 1977. *Ap. J.* 214: 778
Hartwick, F. D. A. 1987. See Gilmore & Carswell 1987, p. 281
Hartwick, F. D. A., Cowley, A. P., Mould, J. R. 1984. *Ap. J.* 286: 269
Hartwick, F. D. A., Sargent, W. L. W. 1978. *Ap. J.* 221: 512
Hauck, B. 1981. *Astron. Astrophys.* 99: 207
Hawkins, M. R. S. 1984. *MNRAS* 206: 433
Hawley, S. L., Jeffreys, W. H., Barnes, T. G. III, Lai, W. 1986. *Ap. J.* 302: 626
Haynes, R., Milne, D., eds. 1991. *The Magellanic Clouds*, *IAU Symp. No. 148*. Dordrecht: Kluwer
Heasley, J. N., Christian, C. A. 1991. See Janes 1991, p. 266
Heck, A. 1978. *Vistas Astron.* 22: 221
Heintz, W. D. 1988. *Publ. Astron. Soc. Pac.* 100: 839
Hernquist, L. 1991. In *Warped Disks and Inclined Rings Around Galaxies*, ed. S. Casertano, P. Sackett, F. Briggs, p. 96. Cambridge: Cambridge Univ. Press
Hernquist, L., Quinn, P. J. 1989. *Ap. J.* 342: 1
Hernquist, L., Quinn, P. 1993. See Majewski 1993a, p. 187
Hesser, J. E., Shawl, S. J., Meyer, J. E. 1986. *Publ. Astron. Soc. Pac.* 98: 403
Hesser, J. E., Harris, W. E., VandenBerg, D. A., Allwright, J. W. B., Schott, P., Stetson, P. B. 1987. *Publ. Astron. Soc. Pac.* 99: 739
Hintzen, P., Oswalt, T. D., Liebert, J., Sion, E. M. 1989. *Ap. J.* 346: 454
Hobbs, L. M., Thorburn, J. A., Rodriguez-Bell, T. 1990. *Astron. J.* 100: 710
Hobbs, L. M., Thorburn, J. A. 1991. *Astron. J.* 102: 1070
Hodder, P. J. C., Nemec, J. M., Richer, H. B., Fahlman, G. G. 1992. *Astron. J.* 103: 460
Iben, I., Laughlin, G. 1989. *Ap. J.* 341: 312
Ipser, J. R., Semenzato, R. 1985. *Astron. Astrophys.* 149: 408
Irwin, M. J. 1991. See Haynes & Milne 1991, p. 453
Isern, J., Mochkovitch, R., García-Berro, E., Hernanz, M. 1991. *Astron. Astrophys.* 241: L29
Isobe, S. 1974. *Astron. Astrophys.* 36: 333
Jahreiss, H., Gliese, W. 1989. *Contrib. Van Vleck Obs.* 8: 11
Janes, K. A. 1988. *Contrib. Van Vleck Obs.* 7: 59
Janes, K. A., ed. 1991. *The Formation and Evolution of Star Clusters*, ASP Conf. Ser. 13. San Francisco: Astron. Soc. Pac.
Jarvis, J. F., Tyson, J. A. 1981. *Astron. J.* 86: 476
Jenkins, A., Binney, J. 1990. *MNRAS* 245: 305
Jones, B. F., Klemola, A. R., Lin, D. C. 1989. *Bull. Am. Astron. Soc.* 21: 1107
Jones, B. J. T., Wyse, R. F. G 1983. *Astron. Astrophys.* 120: 165
Jones, R. V., Carney, B. W., Storm, J., Latham, D.W. 1992. *Ap. J.* 386: 646
Kaluzny, J. 1990. *MNRAS* 243: 492
Kapteyn, J. C. 1922. *Ap. J.* 55: 302
Katz, N. 1992. *Ap. J.* 391: 502
Keenan, D. W., Innanen, K. A. 1975. *Astron. J.* 80: 290
Keenan, P. C., Keller, G. 1953. *Ap. J.* 117: 241
Kinman, T. D. 1959. *MNRAS* 119: 538
Kinman, T. D. 1965. *Ap. J. Suppl.* 11: 199
Kinman, T. D. 1992. In *Variable Stars and Galaxies*, ed. B. Warner, ASP Conf. Ser., 30: 19. San Francisco: Astron. Soc. Pac.
Kinman, T. D., Wirtanen, C. A., Janes, J. A. 1966. *Ap. J. Suppl.* 13: 379
Klemola, A. R., Jones, B. F., Hanson, R. B. 1987. *Astron. J.* 94: 501
Klemola, A. R., Vasilevskis, S. 1971. *Publ. Lick Obs.* 22, part III
Klemola, A. R., Vasilevskis, S., Shane, C. D., Wirtanen, C. A. 1971. *Publ. Lick Obs.* 22, part II
Knude, J., Schnedler Nielsen, H., Winther, M. 1987. *Astron. Astrophys.* 179: 115
Koo, D. C., Kron, R. G., Cudworth, K. M. 1986. *Publ. Astron. Soc. Pac.* 98: 285
Kraft, R. P., Sneden, C., Langer, G. E., Prosser, C. F. 1992. *Astron. J.* 104: 645
Kron, R. G. 1980. *Ap. J. Suppl.* 43: 305
Kroupa, P., Tout, C. A., Gilmore, G. 1991. *MNRAS* 251: 293
Kuijken, K., Gilmore, G. 1989. *MNRAS* 239: 605
Kunkel, W. E. 1979. *Ap. J.* 228: 718
Kunkel, W. E., Demers, S. 1976. *R. Greenwich Obs. Bull.* 182: 241
Kurucz, R. L. 1992. See Barbuy & Renzini 1992, p. 225
Lacey, C. G. 1984. *MNRAS* 208: 687
Lacey, C. G., Ostriker, J. P. 1985. *Ap. J.* 299: 633
Laird, J. B., Carney, B. W., Latham, D. W. 1988a. *Astron. J.* 95: 1843

Laird, J. B., Rupen, M. P., Carney, B. W., Latham, D. W. 1988b. *Astron. J.* 96: 1908

Lance, C. M. 1988a. *Ap. J. Suppl.* 68: 463

Lance, C. M. 1988b. *Ap. J.* 334: 927

Larson, R. B. 1969. *MNRAS* 145: 405

Larson, R. B. 1976. *MNRAS* 170: 31

Latham, D. W., Mazeh, T., Carney, B. W., McCrosky, R. E., Stefanik, R. P., Davis, R. J. 1988. *Astron. J.* 96: 567

Latham, D. W., Mazeh, T., Stefanik, R. P., Davis, R. J., Carney, et al. 1992. *Astron. J.* 104: 774

Layden, A. 1993. See Brodie & Smith 1993. In press

Lee, Y.-W., Demarque, P., Zinn, R. 1993. *Ap. J.* Submitted

Liebert, J., Dahn, C. C., Gresham, M., Strittmatter, P. A. 1979. *Ap. J.* 233: 226

Liebert, J., Dahn, C. C., Monet, D. G. 1988. *Ap. J.* 332: 891

Lin, D. N., Richer, H. B. 1992. *Ap. J. Lett.* 388: L57

Lindblad, B. 1927. *MNRAS* 87: 553

Liu, T., Janes, K. A. 1990. *Ap. J.* 354: 273

Loktin, A. V., Matkin, N.V., Federov, V.V. 1986. *Sov. Astron.* 31: 582

Long, K., Ostriker, J. P., Aguilar, L. 1992. *Ap. J.* 388: 362

Longmore, A. J., Dixon, R., Skillen, I., Jameson, R. F., Fernley, J. A. 1990. *MNRAS* 247: 684

Lu, P. K., Demarque, P., van Altena, W., McAlister, H., Hartkopf, W. 1987. *Astron. J.* 94: 1318

Lutz, T. E. 1986. In *Astrometric Techniques, IAU Symp. No. 109*, ed. H. K. Eichhorn, R. J. Leacock, p. 47. Dordrecht: Reidel

Lutz, T. E., Hanson, R. B., van Altena, W. F. 1988. In *The Extragalactic Distance Scale*, ed. S. van den Bergh, C. J. Pritchet, ASP. Conf. Ser. 4: 170. San Francisco: Astron. Soc. Pac.

Lutz, T. E., Kelker, D. H. 1973. *Publ. Astron. Soc. Pac.* 85: 573

Luyten, W. J. 1974. *Proper Motion Survey with the Forty-Eight Inch Schmidt Telescope XXXVIII.* Minneapolis: Univ. Minn. Press

Luyten, W. J. 1976. *LHS Catalogue.* Minneapolis: Univ. Minn. Press

Luyten, W. J. 1979. *NLTT Catalogue*, Vol. 1. Minneapolis: Univ. Minn. Press (NLTT)

Lynden-Bell, D. 1982. *Observatory* 102: 202

Majewski, S. R. 1992a. *Ap. J. Suppl.* 78: 87

Majewski, S. R. 1992b. See Barbuy & Renzini 1992, p. 61

Majewski, S. R., ed. 1993a. *Galaxy Evolution: The Milky Way Perspective*, ASP Conf. Ser. 49 San Francisco: Astron. Soc. Pac. In press

Majewski, S. R. 1993b. See Majewski 1993a, p. 5

Majewski, S. R., Cudworth, K. M. 1993. *Publ. Astron. Soc. Pac.* In press

Malmquist, K. G. 1936. *Stockholm Obs. Medd. No. 26*

Marsakov, V. A., Shevelev, Yu. G., Suchkov, A. A. 1990. *Astrophys. Space Sci.* 172: 51

Marsakov, V. A., Suchkov, A. A. 1976. *Sov. Astron. Lett.* 2(4): 148

Marsakov, V. A., Suchkov, A. A. 1977. *Sov. Astron.* 21(6): 700

Mathewson, D. 1985. *Sci. Am.* 252(4): 106

Matteuci, F., Tornambé, A. 1985. *Astron. Astrophys.* 142: 13

Mayor, M. 1974. *Astron. Astrophys.* 32: 321

McClure, R. D. 1982. *Ap. J.* 254: 606

Meusinger, H. 1991. *Astrophys. Space Sci.* 182: 19

Meusinger, H., Reimann, H.-G., Stecklum, B. 1991. *Astron. Astrophys.* 245: 57

Mihalas, D., Binney, J. 1981. *Galactic Astronomy.* San Francisco: Freeman

Monet, D. G., Dahn, C. C., Vrba, F. J., Harris, H. C., Pier, J. R., et al. 1992. *Astron. J.* 103: 638

Morgan, W. W. 1956. *Publ. Astron. Soc. Pac.* 68: 509

Morrison, H. L. 1993. *Astron. J.* 105: 539

Morrison, H. L., Flynn, C., Freeman, K. C. 1990. *Astron. J.* 100: 1191

Mould, J. R., Hyland, A. R. 1976. *Ap. J.* 208: 399

Murray, C. A. 1986. *MNRAS* 223: 649

Nemec, J., Nemec, A. F. L. 1991. *Publ. Astron. Soc. Pac.* 103: 95

Nissen, P.E., Schuster, W.J. 1991. *Astron. Astrophys.* 251: 457

Noerdlinger, P. D., Arigo, R. J. 1980. *Ap. J. Lett.* 237: L15

Noh, H.-R., Scalo, J. 1990. *Ap. J.* 352: 605

Norris, J. 1980. In *Globular Clusters*, ed. D. Hanes, B. Madore, p. 113. Cambridge: Cambridge Univ. Press

Norris, J. 1986. *Ap. J. Suppl.* 61: 667

Norris, J. 1987. *Astron. J.* 93: 616

Norris, J. E., Bessell, M. S., Pickles, A. J. 1985. *Ap. J. Suppl.* 58: 463

Norris, J. E., Green, E. M. 1989. *Ap. J.* 337: 272

Norris, J. E., Hawkins, M. R. S. 1991. *Ap. J.* 380: 104

Norris, J. E., Ryan, S. G. 1989a. *Ap. J. Lett.* 336: L17

Norris, J. E., Ryan, S. G. 1989b. *Ap. J.* 340: 739

Norris, J. E., Ryan, S. G. 1991. *Ap. J.* 380: 403

O'Connell, D. J. K., ed. 1958. *Specola Vaticana* 5

Olszewski, E. W., Peterson, R. C., Aaronson, M. 1986. *Ap. J. Lett.* 302: L45

Olszewski, E. W., Schommer, R. A., Aaronson, M. 1987. *Astron. J.* 93: 565

Oort, J. 1958. *Specola Vaticana* 5: 415
Ostriker, J. P., Tremaine, S. 1975. Ap. J. Lett. 202: L113
Pagel, B. E. J. 1992. See Barbuy & Renzini 1992, p. 133
Patterson, R. J., Ianna, P. A. 1991. *Astron. J.* 102: 1091
Peterson, D. M., Solensky, R. 1987. *Ap. J.* 315: 286
Pier, J. 1984. *Ap. J.* 281: 260
Poveda, A., Allen, C., Schuster, W. 1992. See Barbuy & Renzini, p. 471
Preston, G. W. 1959. *Ap. J.* 130: 507
Preston, G. W., Shectman, S. A., Beers, T. C. 1991. *Ap. J.* 375: 121
Proffit, C., Michaud, G. 1991. *Ap. J.* 371: 584
Quinn, P. J., Goodman, J. 1986. *Ap. J.* 309: 472
Quinn, P. J., Hernquist, L., Fullager, D. P. 1992. *Ap. J.* 403: 74
Rana, N. C. 1991. *Annu. Rev. Astron. Astrophys.* 29: 129
Ratnatunga, K. U., Freeman, K. C. 1985. *Ap. J.* 291: 260
Ratnatunga, K. U., Freeman, K. C. 1989. *Ap. J.* 339: 126
Ratnatunga, K. U., Yoss, K. M. 1991. *Ap. J.* 377: 442
Reid, I. N. 1991. *Astron. J.* 102: 1428
Reid, N. 1984. *MNRAS* 206: 1
Reid, N. 1990. *MNRAS* 247: 70
Reid, N. 1992. *MNRAS* 257: 257
Reid, N., Majewski, S. R. 1993. *Ap. J.* 409: 635
Renzini, A. 1991. In *Observational Tests of Cosmological Inflation*, ed. T. Shanks, A. J. Banday, R. S. Ellis, C. S. Frenk, A. W. Wolfendale, p. 131. Dordrecht: Kluwer
Rich, R. M. 1992. See Barbuy & Renzini 1992, p. 29
Richer, H. B., Fahlman, G. G. 1992. *Nature* 358: 383
Richstone, D. O., Graham, F. G. 1981. *Ap. J.* 248: 516
Richstone, D., Gould, A., Guhathakurta, P., Flynn, C. 1992. *Ap. J.* 388: 354
Robin, A., Crézé, M. 1986. *Astron. Astrophys. Suppl.* 64: 53
Rodgers, A. W. 1991. In *Proc. Conf. on Dynamics of Disc Galaxies*, ed. B. Sundelius, p. 29. Göteborg: Göteborg Univ.
Rodgers, A. W., Harding, P., Sadler, E. 1981. *Ap. J.* 244: 912
Rodgers, A. W., Paltoglou, G. 1984. *Ap. J. Lett.* 283: L5
Roman, N. G. 1950. *Ap. J.* 112: 554
Roman, N. G. 1952. *Ap. J.* 116: 122
Roman, N. G. 1954. *Astron. J.* 59: 307
Roman, N. 1965. See Blaauw & Schmidt 1965, p. 345
Rose, J. A. 1985. *Astron. J.* 90: 787
Rose, J. A., Agostinho, R. 1991. *Astron. J.* 101: 950
Rowan-Robinson, M. 1985. *The Cosmological Distance Ladder*, p. 48. New York: Freeman
Ryan, S. G. 1992. *Astron. J.* 104: 1144
Ryan, S. G., Norris, J. E. 1991. *Astron. J.* 101: 1835
Ryan, S. G., Norris, J. E. 1993. See Majewski 1993a, p. 103
Saha, A. 1985. *Ap. J.* 289: 310
Saio, H., Yoshii, Y. 1979. *Publ. Astron. Soc. Pac.* 91: 553
Sandage, A. 1969. *Ap. J.* 158: 1115
Sandage, A. 1981. *Astron. J.* 86: 1643
Sandage, A. 1986. *Annu. Rev. Astron. Astrophys.* 24: 421
Sandage, A. 1990a. *J. R. Astron. Soc. Can.* 84: 70
Sandage, A. 1990b. *Ap. J.* 350: 631
Sandage, A. 1993. *Astron. J.* Submitted
Sandage, A., Cacciari, C. 1990. *Ap. J.* 350: 645
Sandage, A., Fouts, G. 1987. *Astron. J.* 93: 74
Sandage, A., Kowal, C. 1986. *Astron. J.* 91: 1140
Sandage, A. R., Schwarzschild, M. 1952. *Ap. J.* 116: 463
Sandage, A., Walker, M. F. 1955. *Astron. J.* 60: 230
Saradejini, A., Demarque, P. 1990. *Ap. J.* 365: 219
Sarajedini, A., King, C. R. 1989. *Astron. J.* 98: 1624
Sarajedini, A., Lederman, A. 1991. See Janes 1991, p. 293
Scalo, J. M. 1987. In *Starbursts and Galaxy Evolution*, ed. T. X. Thuan, T. Montmerle, J. T. T. Van, p. 445 Gif sur Yvette: Ed. Frontières
Scalo, J. M., Miller, G. E. 1980. *Ap. J.* 239: 953
Schmidt, M. 1975. *Ap. J.* 202: 22
Schuster, W. J. 1990. *Rev. Mex. Astron. Astrof.* 21: 300
Schuster, W. J., Allen, C., Poveda, A. 1992. See Barbuy & Renzini 1992, p. 486
Schuster, W. J., Nissen, P. E. 1988. *Astron. Astrophys.Suppl.* 73: 225
Schuster, W. J., Nissen, P. E. 1989. *Astron. Astrophys.* 221: 65
Schuster, W. J., Parrao, L., Contreras Martinez, M. E. 1993. *Astron. Astrophys. Suppl.* 97: 951
Schwan, H. 1990. *Astron. Astrophys.* 228: 69
Schwan, H. 1991. *Astron. Astrophys.* 243: 386
Schweitzer, A., Cudworth, K. M., Majewski, S. R. 1993. See Brodie & Smith 1993. In press
Searle, L. 1977. In *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley,

R. B. Larson, p. 219. New Haven: Yale Univ. Press
Searle, L., Zinn, R. 1978. *Ap. J.* 225: 357 (SZ)
Silk, J. 1985. *Ap. J.* 297: 9
Sneden, C., Kraft, R. P., Prosser, C. F., Langer, G. E. 1991. *Astron. J.* 102: 2001
Soderblom, D. R., Duncan, D. K., Johnson, D. R. 1991. *Ap. J.* 375: 722
Sommer-Larsen, J., Beers, T. C. 1993. *Bull. Am. Astron. Soc.* 24: 1177
Sommer-Larsen, J., Christensen, P. R. 1987. *MNRAS* 225: 499
Sommer-Larsen, J., Christensen, P. R. 1989. *MNRAS* 239: 441
Sommer-Larsen, J., Zhen, C. 1990. *MNRAS* 242: 10
Soubiran, C. 1992. *Astron. Astrophys.* 259: 394
Spaenhauer, A. 1989. *Contrib. Van Vleck Obs.* 9: 45
Spite, M. 1992. See Barbuy & Renzini 1992, p. 123
Spitzer, L. 1987. *Dynamical Evolution of Globular Clusters*. Princeton: Princeton Univ. Press
Spitzer, L., Schwarzschild, M. 1951. *Ap. J.* 114: 385
Spitzer, L., Schwarzschild, M. 1953. *Ap. J.* 118: 106
Statler, T. S. 1988. *Ap. J.* 331: 71
Stauffer, J. R., Hartmann, L. W. 1986. Ap. *J. Suppl.* 61: 531
Stetson, P. B. 1981a. *Astron. J.* 86: 1337
Stetson, P. B. 1981b. *Astron. J.* 86: 1882
Stetson, P. B., VandenBerg, D. A., Bolte, M., Hesser, J. E., Smith, G. H. 1989. *Astron. J.* 97: 1360
Stringfellow, G. S., Bodenheimer, P., Noerdlinger, P. D., Arigo, R. J. 1983. *Ap. J.* 264: 228
Strömgren, B. 1987. See Gilmore & Carswell, p. 229
Strugnell, P., Reid, N., Murray, C. A. 1986. *MNRAS* 220: 413
Stryker, L.L., Hesser, J. E., Hill, G., Garlick, G. S., O'Keefe, L. M. 1985. *Publ. Astron. Soc. Pac.* 97: 247
Suntzeff, N. B., Kinman, T. D., Kraft, R. P. 1991. *Ap. J.* 367: 528
Taam, R., Kraft, R. P., Suntzeff, N. 1976. *Ap. J.* 207: 201
Taff, L. G. 1989. *Astron. J.* 98: 1912
Taff, L. G., Lattanzi, M. G., Bucciarelli, B. 1990. *Ap. J.* 358: 359
Tinsley, B. M., Larson, R. B. 1979. *MNRAS* 186: 503
Toomre, A. 1977. In *The Evolution of Galaxies and Stellar Populations*, ed. B. M. Tinsley, R. B. Larson, p. 401. New Haven: Yale Univ. Press
Tóth, G., Ostriker, J. P. 1992. *Ap. J.* 389: 5
Trumpler, R. J., Weaver, H. F. 1953. *Statistical Astronomy*, p. 369. Berkeley: Univ. Calif. Press
Truran, J. W., Thielemann, F. K. 1987. In *Stellar Populations*, ed. C. A. Norman, A. Renzini, M. Tosi, p. 149. Cambridge: Cambridge Univ. Press
Tsikoudi, V. 1979. *Ap. J.* 234: 842
Tsikoudi, V. 1980. *Ap. J. Suppl.* 43: 365
Tucholke, H.-J., Hiesgen, M. 1991. See Haynes & Milne 1991, p. 491
Twarog, B. A. 1980. *Ap. J.* 242: 242
Twarog, B. A., Anthony-Twarog, B. J. 1989. *Astron. J.* 97: 759
Upgren, A. R., Weis, C. W., Fu, H.-H., Lee, J. T. 1990. *Astron. J.* 100: 1642
Upgren, A. R., Zhao, H., Lee, J. T. 1992. *Astron. J.* 104: 1203
van Altena, W. F. 1974a. *Astron. J.* 79: 826
van Altena, W. F. 1974b. *Publ. Astron. Soc. Pac.* 86: 217
van Altena, W. F., Lee, J. T. 1989. *Contrib. Van Vleck Obs.* 8: 83
van Altena, W. F., Lee, J. T., Hanson, R. B., Lutz, T. E. 1988. *Contrib. Van Vleck Obs.* 7: 175
van Bueren, H. G. 1952. *Bull. Astron. Inst. Neth.* XI: 385
VandenBerg, D. A. 1985. *Ap. J. Suppl.* 58: 711
VandenBerg, D. A. 1991. See Janes 1991, p. 183
VandenBerg, D. A., Bolte, M., Stetson, P. B. 1990. *Astron. J.* 100: 445
VandenBerg, D. A., Bridges, T.J. 1984. *Ap. J.* 278: 679
van den Bergh, S. 1993. *Astron. J.* 105: 971
van der Kruit, P. C., Searle, L. 1981a. *Astron. Astrophys.* 95: 105
van der Kruit, P. C., Searle, L. 1981b. *Astron. Astrophys.* 95: 116
Vaughan, A. H., Preston, G. W. 1980. *Publ. Astron. Soc. Pac.* 92: 385
Villumsen, J. V. 1985. *Ap. J.* 290: 75
von Hippel, T. A. 1992. *Astron. J.* 104: 1765
von Hippel, T., Bothun, G. D. 1993. *Astron. J.* Submitted
von Weizsäcker, C. F. 1951. *Ap. J.* 114: 165
Vorontsov-Velyaminov, B. A. 1977. *Observatory* 97: 204
Vyssotsky, A. N., Williams, E. T. R. 1944. *Astron. J.* 51: 4
Wallerstein, G. 1962. *Ap. J. Suppl.* 6: 407
Wayte, S. R. 1991. See Haynes & Milne 1991, p. 453
Weis, E. W. 1991. *Astron. J.* 101: 1882
Wesselink, T. 1987. *A Photometric Study of Variable Stars in a Field near the Galactic Center*. Nijmegen: Braldsenstein
Wheeler, J. C., Sneden, C., Truran, J. W. 1989. *Annu. Rev. Astron. Astrophys.* 27: 279
Wielen, R. 1974. *Highlights Astron.* 3: 395
Wielen, R. 1977. *Astron. Astrophys.* 60: 263

Wielen, R., Dettbarn, C., Fuchs, B., Jahreiss, H., Radons, G. 1992. See Barbuy & Renzini 1992, p. 81
Wildey, R. L., Burbidge, E. M., Sandage, A. R., Burbidge, G. R. 1962. *Ap. J.* 135: 94
Winget, D. E., Hansen, C. J., Liebert, J., Van Horn, H. M., Fontaine, G., et al. 1987. *Ap. J. Lett.* 315: L77
Woltjer, L. 1975. *Astron. Astrophys.* 42: 109
Wood, M. A. 1992. *Ap. J.* 386: 539
Woolley, R., Epps, E. A., Penston, M. J., Pocock, S. B. 1970. *R. Obs. Ann. 5*
Wyse, R. F. G., Gilmore, G. 1986. *Astron. J.* 91: 855
Wyse, R. F. G., Gilmore, G. 1988. *Astron. J.* 95: 1404
Wyse, R. F. G., Gilmore, G. F. 1989. *Comments Astrophys.* 13: 135
Wyse, R. F. G., Gilmore, G. F. 1990. In *Chemical & Dynamical Evolution of Galaxies*, ed. F. Ferrini, J. Franco, F. Matteucci, p. 19. Pisa: ETS Editrice
Wyse, R. F. G., Gilmore, G. 1993. See Brodie & Smith 1993. In press
Yoshii, Y., Saio, H. 1979. *Publ. Astron. Soc. Jpn.* 31: 339
Yoshii, Y., Ishida, K., Stobie, R. S. 1987. *Astron. J.* 93: 323
Yoss, K. M. 1992. *Astron. J.* 104: 327
Yoss, K. M., Neese, C. L., Hartkopf, W. I. 1987. *Astron. J.* 94: 1600
Yuan, J. W. 1989. *Astron. Astrophys.* 224: 108
Zaritsky, D., Olszewski, E. W., Schommer, R. A., Peterson, R. C., Aaronson, M. 1989. *Ap. J.* 345: 759
Zinn, R. 1985. *Ap. J.* 293: 424
Zinn, R. 1993. See Brodie & Smith 1993. In press