The Halo Populations

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Abstract.

Understanding the halo populations of the Milky Way impacts upon a vast landscape of stellar, Galactic and extragalactic astrophysics. Topics likely to play important roles at this meeting are introduced, including aspects of properties of the outer halo, the halo-to-disc transition, globular cluster binary stars and dynamics, chemistry, and age determinations.

1. Overview

"Stellar populations in the Galactic halo" is an exceedingly broad topic affecting nearly all aspects of this Symposium in one way or another. The primary goal of this introduction is to identify themes likely to be amplified and, with fortune, clarified by others. The topics were chosen based on my perception of their ultimate relevance to our understanding of galaxies and galaxy formation. While the emphasis is on work of the last two years or so, it is so extensive that many worthy achievements must be ignored due to space limitations.

To set the scene, it is well known but easy to forget that the Galaxy has undergone dramatic evolution and is, in every sense of the words, a very dynamic entity. Its halo *appears* to be sparsely populated. The known mass associated with visible light accounts for only a few percent of the total estimated mass of the Galaxy. A series of major questions, however, remain unanswered about the mysterious (but see Kurucz 1991) dark matter commongly thought to dominate the mass and dynamics of the Galaxy. In particular, what is its spatial distribution? Does *visible* halo matter trace *dark* halo matter? Is dark matter baryonic, after all?

How big is our halo? We know of individual stars at $R_{gc} \gtrsim 50$ kpc (§2.1), which is comparable to the distances of the Magellanic Clouds, who themselves are contained in the Galactic halo. We know of globular star clusters extending out to some 120 kpc, and we know of dwarf spheroidal galaxies at ~250 kpc. Certainly all of these objects are current constituents of the Galactic halo (but remember the initial caveat about not viewing the Galaxy as a static entity). *If* the bound halo extends to such great distances, is it reasonable for galaxy formation theories to use R_{max} values of 30 kpc?

Throughout the halo, chemical composition, as characterized by the logarithmic metals-to-hydrogen ratio relative to the Sun, [M/H] (where M refers to generic heavy elements, usually of the Fe peak), spans three or more dex, with a wide range at each R_{gc} zone. Does the halo possess an [M/H] gradient? Are there element abundance-ratio differences between halo and disc populations, or between halo cluster and halo field stars? Are there zero-metal stars in the halo?

To what extent are the halo populations we observe today representative of the original halo populations? How similar were the latter to those probed by absorption line systems of distant quasars? Are globular cluster and field halo stars drawn from the same parent population? What roles do dynamical processes play in cores of star

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clusters (and are they perhaps relevant to activity hidden from view in the cores of, say, elliptical galaxies)? What roles did R_{gc} or z-height play in star formation within the halo and its globular clusters? How, where, and at what [M/H] does the halo join onto other Galactic components? Is a 'thick disc' unambiguously present and, if so, is there significant overlap between it and the halo?

Perhaps when more of these questions are answered, we will know what is meant by the title of my talk. In the meantime, my aim is to examine some recent efforts that address aspects of these questions. The interested reader will find considerable recent information in Janes (1991), and will find Gilmore, King and van der Kruit (1990) or Larson (1990) invaluable for placing it in context.

2. The Outer Halo

The very sparseness of the visible halo makes its study particularly challenging. There are simply too few globular star clusters to trace all aspects of early Galactic evolution, especially when, of the total ~150 objects (see, *e.g.,* Webbink 1985), perhaps only ~75% can be identified with the 'true' halo (§3.1). In order to make progress, field halo stars must be identified. In the past decade, increasing emphasis has been placed upon *in situ,* chemical and kinematical surveys of the halo field populations. The power of such surveys to resolve questions of size, shape, parentage and role of the 'second parameter' in the halo populations was driven home to me by Freeman at Patras (see, *e.g.,* Freeman 1983, Ratnatunga and Freeman 1985), but many others were then, and now, pursuing surveys of enormous importance (*e.g.,* Beers, Preston and Shectman 1985, 1991, Bothun, *et al.* 1991, Croswell, *et al.* 1991, Grenon 1989, 1991, Rose and Agostinho 1991, Ryan and Norris 1991a,b, Sandage and Fouts 1987, Schuster and Nissen (1989), Suntzeff, Kinman and Kraft 1991...). The importance of understanding selection biases in such surveys cannot be overstressed. Moreover, 'consumers' should appreciate that the surveys are difficult and time consuming: for instance, only one star in a thousand examined by Beers, *et al.* turns out to have low [M/H].

2.1. Spatial Extent

Individual stars are known at distances of 50 kpc (Ciardullo, Jacoby and Bond 1989), globular clusters at more than 100 kpc and dwarf spheroidals (dSphs) at more than 200 kpc. It seems probable that individual stars will ultimately be identified at distances intermediate between 50 kpc and the outermost globulars or dSphs. Most analyses of velocity ellipsoids and of field star and cluster counts infer the halo to be nearly round in shape for $R_{gc} \gtrsim 20$ kpc. They also find that the stellar volume density varies as $R_{gc}^{-3.5}$. As R_{gc} decreases in the halo, its subsystems become increasingly velocity anisotropic and flattened (see, *e.g.,* Hartwick 1987, Preston, Shectman and Beers 1991, Sommer-Larsen, Christensen and Flynn 1991, and Vedel and Sommer-Larsen 1990).

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2.2. Chemical Composition

Deciding whether or not there is a gradient in chemical composition as a function of R_{gc} within the Galactic halo requires field star samples: the globular clusters are again too few. In the seminal Lick RR Lyrae survey, Suntzeff, Kinman and Kraft (1991) find no evidence for such a gradient with respect to R or |z| outside the solar circle, but within it find Δ[M/H]~ -0.06 dex kpc^{-1} (see their figures 4, 5). They find the metallicity distribution function of the field and cluster RR Lyrae stars to be the same over the entire range of R_{gc} sampled. However, they note some differences when comparing the metallicity distribution of the entire globular cluster system to that of field RR Lyraes: for $R>R_o$, [M/H] and its dispersion are indistinguishable, while for $R<R_o$ the field RR Lyraes are more metal rich than the globular clusters. They also find that the field variables obey a period-shift, metallicity relation similar to that of the cluster variables. Assuming the populations to be the same, they estimate that 2% of the halo mass is locked up in globulars and that the mass of the luminous halo within 4-25 kpc is $\sim 9 \times 10^8 M_\odot$.

A sample of 372 field subdwarfs with [M/H] and v_r determinations has been extensively modelled by Ryan and Norris (1991a,b); their database includes the stars studied by Laird, *et al.* (1988). For stars with [M/H]< -1.4 (presumably a nearly pure halo sample), they find no correlation between kinematics and [M/H] except for an increase in σ_W as [M/H] decreases. The metallicity distribution appears to be in good agreement with a simple model (Hartwick 1976) over 2.5 decades in [M/H]. They argue that Searle's (1977) stochastic model for the formation of the Galaxy does not appear to match the field star data closely, but could account for the globular cluster properties if some ten enrichments per fragment had occurred. They further argue that it is possible, but not established, that field halo stars and globular clusters have different parent populations.

A characteristic long associated with the outer halo is the so-called 'second parameter effect': a discord between [M/H]s inferred from the form of the horizontal and giant branches for individual globular clusters and dSphs. During the past two years, age differences have received significant observational support as constituting a major component of the second parameter phenomenon in star clusters (see, *e.g.*, Bolte 1989, Green and Norris 1990, Lee, Demarque and Zinn 1990, VandenBerg, Bolte and Stetson 1990, Sarajedini and Demarque 1990). These studies suggest that there *may* be a modest age, metallicity relation in the Galaxy, with the oldest objects being more deficient in heavy elements.

Another advance stemming from increased survey activity has been the alleviation of the apparent paucity of extremely metal-deficient G dwarfs in the solar neighborhood described provocatively by Bond (1981). Beers (1991) and Ryan and Norris (1991a,b), among others, suggest that the metallicity distribution of the Galactic halo stars remains rather flat to [M/H]~ -4.5, the lowest levels measured. Such results seem consistent with a simple model of Galactic chemical evolution (Hartwick 1976). For me, recent research has strengthened evidence that globular clusters and field stars in the Galactic halo may be from the same parent populations. However, recall that colors of globular cluster systems around ellipticals suggest that their average composition at a particular radius is lower than that of the underlying halo light (Harris 1991).

2.3. Luminosity Functions

Studies by Richer, Fahlman and their collaborators have apparently pushed I-band luminosity functions to within hundreths of a solar mass of the expected brown dwarf domain (*e.g.,* Richer, *et al.* 1991). Some, and possibly all, of the clusters they have observed exhibit very steep mass functions below $\sim 0.4\ M_\odot$, from which they suggest that perhaps the mysterious halo dark matter is composed of Population II objects. Fall and Rees (1985), Aguilar, Hut and Ostriker (1988), Chernoff and Weinberg (1990) and others suggest that the present day clusters may be but a small fraction of the original population. Such concepts may be consistent with recent observations suggesting that weak clustering and/or dissolution is occurring in the halo. Sommer-Larsen and Christensen (1987) believe they have discovered a distant group of stars in the process of dissolving, while Doindus and Beers (1989) find statistical evidence for field horizontal branch candidate stars lying 5-8 kpc from the Sun to cluster on $r \lesssim 25$ pc scales. Thus, if copious low-mass star formation occurred in metal deficient material (Zinnecker 1987), as Richer, *et al.* 's data suggest, the halo dark matter may be composed of low-mass stars originally formed in clusters (see also Ashman 1990). Richer, *et al.* note that their results are subject to at least one important caveat: the upturn in inferred mass-function slope occurs disturbingly close to the slope change in the theoretical M/L relation. Nonetheless, this is an observational opportunity clearly deserving attention in the era of giant ground-based telescopes (and of second-generation HST cameras).

3. Transition from Halo to Disc

If the thick disc exists as a discrete component of the Galaxy, was it formed by mergers, by collapse, or by upwards scattering? Are the halo and the thick disc distinct and, if so, what values of [M/H], R_{gc}, z, etc. characterize the transition region? What effect does superbubble ejection of disc gas into the halo and thick disc (Heiles 1991, De Geus 1991) have on Galactic evolution? In my mind, such intriguing questions form the backdrop to any discussion of the inner halo.

3.1. Spatial Extent

Empirically, the systemic luminosity function for the Galactic globular clusters, as for the cluster systems of other galaxies, is reasonably well described by a gaussian with $<M_V> \sim -7.4$ and $\sigma \sim 1.3$ (see, *e.g.,* Harris 1991). However, at least one important subsystem, first suspected by Kinman (1959), exists. Zinn (1985), Hesser, Shawl and Meyer (1986) and Armandroff and Zinn (1988) demonstrated that about a quarter of the globulars form a separate, disc-like subsystem. An excellent review by Zinn (1991) summarizes present understanding of this division, and the possibility that a bulge subsystem may also be present. The disc globulars exhibit average features similar to those commonly associated with the stellar thick disc (Table 1).

TABLE I
Globular Cluster and Stellar Populations (Zinn 1991)

	Halo		Thick Disk	
	Stellar	Cluster	Stellar	Cluster
<[Fe/H]>~	−1.7	−1.6	−0.5	−0.5
V_{rot} (km/s)	30 ± 10	43 ± 29	180 ± 10	193 ± 29
σ_{los} (km/s)	110 ± 10	116 ± 11	60 ± 10	59 ± 11

An important constraint on formation and evolution within the halo subsystems may be emerging from the range of slopes of the initial mass functions inferred for upper main sequence stars in globular clusters. The inference of a true initial mass function from observational data requires correction for internal (*e.g.*, Pryor, Smith and McClure 1986) and external (*e.g.*, Stiavelli, *et al.* 1991) dynamical effects, which is not necessarily straightforward. Those corrections notwithstanding, the range of inferred slopes was recently found to correlate better with |z| or R_{gc} (Capaccioli, Ortolani and Piotto 1991), than with [M/H] (McClure, *et al.* 1986, Hesser 1988). Such inferences suggest that gradients within the halo and transition regions may have been set up by a combination of external and internal dynamical processes.

3.2. Chemical Composition

The difficulty of cleanly identifying possible components of the field star populations, even when good kinematic and chemical data are available, is impressive. In particular, the characterization of roughly where the true halo is overtaken by the purported thick disc remains ill defined.

Morrison, Flynn and Freeman (1990) find many stars with thick disc kinematics at [M/H]~ −1.6, i.e., nearly a dex more metal deficient than the mean thick disc population. This may be related in some fashion to Carney, Storm and Jones' (1991) evidence among RR Lyrae stars for a sudden population change at [M/H]~ −1.7. Rees and Cudworth (1991) showed that the globular cluster M28 (NGC 6626) has a disc-like orbit, lies at z~ 0.3 kpc, yet has [M/H]~ −1.7. Latham (1991) reports that he and his collaborators find stars in their *in situ* surveys of v_rs and [M/H]s for ~1300 objects that exhibit solar metallicities and halo kinematics, and vice versa, leading naturally to the question, 'what are they?'. The extensive Geneva photometric and radial velocity surveys summarized by Grenon (1991) find halo and bulge stars in the solar neighborhood, with the clear implication that models of the Galaxy must be modified to include *radial* interchange of stellar populations.

For field horizontal branch stars, Preston, Shectman and Beers (1991) interpret a small color gradient, in the sense that $<(B-V)_o>$ becomes redder by ~0.025 mag per 2 kpc as one proceeds from 2 to 12 kpc in the halo, as evidence for a decrease in the mean age of such stars as one proceeds outward into the halo. They also suspect an increase in the range of ages as one moves outwards over that interval.

In general the stars in the above mentioned surveys can be reasonably assumed to be relatively old. Fitzsimmons, *et al.* (1991), Conlon, *et al.* (1990, 1991), and Quin *et al.* (1991) all report high latitude B stars, some of which appear to be

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normal Population I objects at $2 \lesssim z \lesssim 25$ kpc. If they are not nearby, subluminous objects with spectra mimicing normal stars (*e.g.,* Waelkins, *et al.* 1987, Tobin 1987), were they ejected from disc clusters or formed at high Galactic latitude? Evidence for recent star formation in the vicinity of the optical 'jet' in the halo of NGC 5128 (Graham 1975, Osmer 1978) remains for me a sober reminder that galaxy halos may represent more complex mixtures than some of us enjoy contemplating.

The confusing evidence regarding the characterization of the transition region notwithstanding, the data presently available admit the concept of a metal-deficient halo joining onto a more enriched thick disc subsystem (see especially Majewski (1991), of which I was unaware when I spoke). However, the mixture models of Nemec and Nemec (1991 and this volume) illustrate how very difficult, indeed, it is to formulate unambiguous descriptive parameters for Galactic subsystems.

4. Binaries, Dynamics and Exotica

Besides their frequency being almost certainly a fundamental characteristic of a stellar population, binaries are an important source of energy that can retard or prevent dynamical collapse in the cores of globular clusters, and that provide channels to form unusual stars. When integrated over the Galactic lifetime, internal and external dynamical processes (*e.g.,* collisions, mergers, tidal shocks) are clearly relevant to understanding how observations today relate to properties of the original halo population (see Djorgovski 1991 for a clear review). Moreover, the study of present-day 'exotica' in globular clusters may bear strongly upon our ultimate understanding of the field halo populations, particularly if theoretical arguments (§2.3) for a much larger cluster system in the early Galaxy are valid. Finally, such physics seems intrinsically worthy of study, for how can we hope to understand, say, elliptical galaxies, if we cannot realistically model the simplest dynamical systems known, the Galactic globular clusters?

4.1. Field Halo Binaries

In Buenos Aires, Latham (1991) announced that his radial velocity surveys carried out over a decade with Carney and collaborators now yield ~150 halo binary systems for which they have been able to determine orbits. This is quite simply a *tour de force* observational result! They find a similar, ~20% binary frequency among their Population II samples as in their studies of Population I samples. They also have reasons to infer in all of their samples that the secondaries are drawn from normal field populations, which suggests that the predominant formation mechanism is likely to be capture and/or collision, rather than fission.

4.2. Evidence for Binaries in Globular Clusters

The dramatic rise in evidence for a significant binary component in at least some globular star clusters continues unabated. Due to their potential influence on cluster evolution (*e.g.,* Goodman and Hut 1989, McMillian, Hut and Makino 1990), it seems appropriate to update that evidence.

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Again in Buenos Aires, Meylan (1991; see also Paresce, *et al.* 1991) reported evidence for 21 blue stragglers within a $26 \times 26''$ frame of the center of 47 Tucane secured with HST's Faint Object Camera. This is, of course, a region of the cluster that remains largely unexplored from the ground, due to image crowding; obvious blue straggler candidates at larger radii are essentially lacking in published color-magnitude diagrams (*e.g.,* Hesser, *et al.* 1987). Meylan and his collaborators argue that these newly discovered blue stragglers, the central X-ray sources, the millisecond pulsars (Manchester, *et al.* 1991), and two stars thought to be in the process of ejection from the core (Meylan, Dubath and Mayor 1991), are all consistent with close encounters with binaries in a dense core.

In NGC 5466, Mateo, *et al.* (1990, and Nemec's contribution elsewhere herein) have identified nine variable blue stragglers, three of which are eclipsing binaries, with the remaining six being SX Phe pulsators. They suggest that all non-eclipsing blue stragglers in this cluster (and others) may have been formed by mergers of single stars. Astro I observations of ω Centauri, by O'Connell and his colleagues (1991) reveal numerous ultraviolet bright stars, whose nature remains to be explained.

Bailyn (1991) thoroughly reviews the arguments that neutron star binaries (low mass X-ray binaries: LMXRBs) are more common in globular clusters than in the field, thus leading to the expectation that cataclysmic variables (CVs) will be numerous in clusters. However, Cederbloom, *et al.* (1991) find the inner $6.6''$ of M15 (thought to be a post-core-collapse cluster) to be bluer in B−V yet stronger in Hα absorption than at larger radii. This seems to imply that the excess blue light does not arise from CVs (see §4.3)

In a burgeoning field of research, available data led Kulkarni, Narayan and Romani (1990) to estimate that there may be as many as $\sim 10^4$ millisecond pulsars in Galactic globulars. Prince, *et al.* (1991) postulate that 2127+11C, the eight hour binary pulsar in M15, is being ejected following a close encounter with another binary, a mechanism that may populate the field with such pulsars. Relativistic winds from millisecond pulsars may be responsible for ejecting cold gas from globulars (Spergel 1991); note that HI gas may have been, at last, detected in the process of ejection from NGC 2808 (Faulkner, *et al.* 1991).

As reviewed elsewhere (Hesser 1988, 1991), some globular cluster color-magnitude diagrams exhibit photometric evidence for a sequence of roughly equal-mass binaries more luminous and cooler than the single-star main sequence. While residual widths in the observed main sequences of M92 and M30 may arise in part from crowding (see, *e.g.,* Stetson and Harris 1988), modelling is consistent with a binary frequency of 9 and 4%, respectively (Romani and Weinberg 1991) in the outer regions where the data were obtained. Murray, Clarke and Pringle (1991) have suggested that if all stars formed simultaneously as single stars, the protostellar discs would increase the interaction cross sections during cluster collapse, thus leading to the establishment of at least a few percent of 'primordial' binaries. The radial velocity surveys of Pryor, *et al.* (1989) appear to be consistent with such percentages. On the other hand, Bolte (1991) reports a 10% main-sequence binary fraction with primary to secondary mass ratio ≤ 1.4 at $3r_c$ in NGC 288. This implies a much larger total binary percentage if all mass ratios are considered.

4.3. Color Gradients in Clusters

One of the most puzzling, and potentially important, observations regarding the structure of globular clusters is the finding by Djorgovski, *et al.* (1991) that clusters with pronounced central cusps (presumably reflecting their condition as post core-collapsed objects) are bluer towards the center, resulting from a demise of red giant branch stars and/or of subgiants, although an increase in the number of blue stragglers could contribute, as well. On the other hand, in NGC 6171, Ferraro, *et al.* (1991) find red giant branch stars to be more centrally concentrated!

4.4. General Remarks

In his review at Buenos Aires, Meylan (1991) noted that the latest determinations of velocity dispersions, masses and M_Vs for old clusters in the Milky Way, the Large Magellanic Cloud and the Fornax dwarf spheroidal now overlap, thus stressing the similarities of clusters found (and probably formed) in quite different environments.

5. Halo Chemistry and Ages

5.1. Chemical Abundance Ratios

Unravelling globular cluster ages is tied to understanding element ratios as a function of [M/H], and to knowing how measurements of the brighter stars relate to the ratios, presumably primordial, exhibited by main sequence stars too faint for study. Alternatively, it is essential to understand if it is meaningful to adopt trends found among more readily measured halo field stars for application to age determinations of globular clusters. The role of [O/Fe] in globular cluster ages has been stressed by VandenBerg (1988) and VandenBerg and Stetson (1991), while another point of view is presented by Straniero and Chieffi (1991) and Chieffi, Straniero and Salaris (1991). Characterizing the selective [O/Fe] enhancement relative to [M/H] in field stars throughout the halo has been a focus of recent research, but [O/Fe] is very difficult to measure in globular cluster stars.

From measurements of the permitted, high-excitation OI triplet at 7771-75Å for 30 metal-deficient G dwarfs, Abia and Rebolo (1989) inferred a strong, nearly monotonic increase in [O/Fe] as [M/H] decreases. Their results differ from those obtained by Barbuy (1988 and this volume) and by Barbuy and Erdelyi-Mendes (1989) using the forbidden [OI] line at 6300Å in K giants. Spiesman and Wallerstein (1991) and Brown, *et al.* (1991) present evidence from both field and cluster stars that also counters the Abia and Rebolo results. Specifically, analysis of ω Cen giants allowed Brown, *et al.* to demonstrate that, over the range $-2.0 \leq$[Fe/H]≤ -1.0, [O/Fe] vs. [M/H] is very similar to that found by Barbuy for field halo giants; similar results were obtained from lower signal-to-noise data by Paltoglou and Norris (1989). Interestingly, Brown, *et al.* remark that the metallicity enrichment processes appear to have been similar in ω Cen ($M \sim 3 \times 10^6 M_\odot$) and the Galactic halo ($\sim 10^9 M_\odot$).

A particularly compelling study was described at Buenos Aires by Bessell (see Bessell, Sutherland and Ruan 1991). They have determined [O/Fe] for a sample of metal-poor G dwarfs in two independent ways: via the near ultraviolet OH lines and via the permitted OI triplet. Their OH results agree well with those of, *e.g.*, Barbuy and her collaborators, while the OI lines agree with Abia and Rebolo. The OH lines are formed in the same layers of the atmospheres as the majority of the metal lines. Consequently, they believe the lower oxygen enhancements deduced from them represent the actual abundances, while they attribute the OI results to real metal-poor stellar atmospheres being hotter in deeper layers than the models. In a potentially related study by Lambert (1991), evidence that forbidden and molecular lines of C and O yield more reliable results than permitted ones leads him (and others) to suspect systematic errors in the model atmospheres for metal-poor stars. Should that be so, *all* abundance determinations using those atmospheres may well be in error and Galactic chronology made even more uncertain.

Bessell and collaborators draw two important conclusions regarding the halo populations. First, that [O/Fe]$\sim$[α/Fe] throughout (Lambert (1991) summarized additional support for this result). Second, that the rise in oxygen enhancement from zero near solar metallicities reaches a plateau, [O/Fe]$\sim +0.5$-0.6, around [M/H]~ -1.6 instead of at ~ -1.0, as commonly reported.

Another constraint on Galactic formation is inherent in the observation by Sneden and his collaborators (see, *e.g.*, Gilroy, *et al.* 1988 and the review by Cowan, Thielemann and Truran 1991) that, among metal deficient stars, heavy element formation has been predominantly by the r-process, whereas among disc stars it has been by a mixture of r- and s-processes. Interestingly, the dispersion in heavy element abundances is generally found to be less than observational errors for stars with [M/H]≤ -1, except for the rare earth elements, where the dispersion is an order of magnitude greater than the observational errors. Within individual globular clusters the small spread in abundances for elements heavier than the CNO group constitutes a very strong constraint on the formation and subsequent evolution of such clusters (Murray and Lin 1990, Truran, Brown and Burkert 1991).

5.2. Ages

Renzini (1991) and Rood (1990), among others, emphasize that uncertainities in (m$-$M) determinations dominate uncertainties in cluster ages. [M/H] uncertainties are important for the handful of subdwarfs used for comparison with cluster color-magnitude diagrams. All calibrations of M_v^{RR} as a function of [M/H] depend intimately upon theory (Renzini), while model colors remain uncertain (VandenBerg 1991). Significant theoretical progress by Pinsonneault, Kawaler and Demarque (1990) demonstrated that rotation is unlikely to affect present age determinations. However, He diffusion can lower the inferred ages by 5-10% with respect to those estimated using standard models (Deliyannis and Demarque 1991, Proffitt and VandenBerg 1991). Deliyannis and Demarque showed from consideration of Li that neglecting He diffusion has probably not caused significant age errors.

A major conceptual breakthrough occurred in 1989 regarding techniques for *relative* age determinations throughout the Galactic halo (VandenBerg, Bolte and Stetson 1990, Sarajedini and Demarque 1990). By use of the color difference between the turnoff region and the base of the red giant branch, relative ages can be determined accurately within modest ranges of [M/H]. Paltoglou and Bell (1991) have shown that with optimized filter selection the [M/H] range may be extended. Hatzidimitriou (1991) suggests that a color difference between the mean color of the red horizontal and of the red giant branches at the same luminosity may serve the same purpose for clusters with [M/H]$\gtrsim -1.7$.

The key results of the recent *relative* age determinations are: a) Among metal-poor clusters, age differences are $\lesssim 0.5$ Gyrs (VandenBerg, Bolte and Stetson 1990; van Albada, Dickens and Wevers 1981; Heasley and Christian 1991), with the possible exception of Ru106, which Buonanno, *et al.* (1991) find to be younger. (I suspect there is some inconsistency between this result, and that of Preston, Shectman and Beers (1991) regarding the field horizontal branch stars.) b) Among globulars of intermediate [M/H], there are objects exhibiting a spread in ages of ~3 Gyrs (VandenBerg, Bolte and Stetson). The key pair of clusters here is NGC 288 and NGC 362, which have identical properties to within the errors of present measurements. However, Dickens, *et al.* (1991) suggest that the stars of NGC 362 exhibit more extensive mixing than do those of NGC 288, which I find quite worrisome. c) Among the metal-rich clusters, Hatzidimitriou (1991) reports a surprisingly large range of ages (~6 to 16 Gyrs). If true, this would eliminate any age gap between 'halo' (thick disc?) clusters and the oldest open clusters. Furthermore, in the younger clusters one would expect to see carbon stars. However, it would seem worthwhile to examine whether differential reddening and/or field star contamination might be affecting her initial age inferences with this promising technique.

It is rather discouraging that with all the improvement in color-magnitude diagrams and theory, there is still such a large uncertainity in the cosmologically important age of the oldest clusters in the Galaxy. Most experienced practitioners agree that with available models the minimum age for metal-poor globulars is not likely to be less that 14 Gyr. But the real errors are large, systematic and difficult to quantify. Hence, we probably cannot decide at this time if the formation of the halo was by a Searle-Zinn (1979), Tinsley-Larson (1979), Toomre (1977) type of subunit merger; by a modified Eggen, Lynden-Bell and Sandage (1962; see also Sandage 1990) collapse; or, as seems likely to me, by some combination thereof.

6. 'Final' Impressions

'Final' impressions from my study of the recent literature are the 'initial' ones with which I go into this conference (my feelings about one of the following was changed during the meeting, but this text closely reflects what I said):

Extragalactic globular cluster systems suggest there may be important relative differences in formation paths. Couture, Harris and Allwright (1991) find that the relative importance of mergers and dissipative collapse apparently can vary among elliptical galaxies that today look structurally similar.

In spite of impressive new data sets and sophisticated analyses, I cannot tell if the halo-to-disc transition is smooth, or clearly separable into discrete (but extensively overlapping?) components; further *in situ* surveys are essential.

Exploration of the effects of the new Livermore interior, and Kurucz astmospheric, opacities deserves priority in the next few years, and is rumored likely to modify significantly some cherished impressions.

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Globular cluster cores are 'gold mines' for study of exotic stars and dynamical astrophysics; they are natural targets for adaptive optics and HST.

One believable, precise E(B−V) determination for a globular cluster is worth ten color magnitude diagrams for it; the larger E(B−V) is, the more weight this statement deserves. Attempts to decide the chronology of early Galactic formation may ultimately hinge on determining reliable reddenings for bulge clusters.

Once upon a time, I thought globular clusters and stellar populations in the Galactic halo were relatively simple...how naive I was! But if they are much more complicated than they once appeared (at least to me), it raises an interesting query at the outset of our meeting: how much fundamental astrophysics is being 'swept under the rug' in our studies of halo and bulge properties of the nearest galaxies, when even nearer, purportedly simpler, globular clusters hold so many surprises?

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DISCUSSIONS

Mateo: You comment that the steep mass function slopes in globular clusters may help explain the dark matter problem with a baryonic solution. However, the M/L's of globular clusters are always among the *lowest* observed in halo environments (*e.g.,* M/L_V's > 10 are common for the outer parts of galaxies and for dSph galaxies). Thus, these steep slopes seem to make the problem worse, implying an even steeper slope for these non-globular cluster populations if you want to use baryons to explain the dark matter.

Hesser: You may well be correct. However, over ~ 15 Gyrs we have reasons to believe that many globulars have been dissolved (*cf.* Fall and Rees 1985, Aguilar, Hut and Ostriker 1988; Chernoff and Weinberg 1990). Moreover, internal dynamical evolution may have modified the original properties of the clusters substantially.

Mould: If the mass function of globular clusters has been modified by dynamical processes, we should be counting halo M dwarfs at 25th magnitude in the field in order to determine the initial mass function of the halo.

Hesser: That would be an excellent thing to do! I assume that in about a year, when the Keck Telescope goes into routine operation, you will be doing it?

Mould: You might assume that!

Ostriker: Note that not only have we lost a signficant fraction of the globular clusters initially in the Galaxy, but also, in the surviving clusters, it is possible that a large fraction of the low mass stars have been lost, especially from the inner parts from which most of our data come.

Hesser: You drive home how much we have to learn about the dynamical history of globulars.

Zinnecker: I am wondering about the effects of stellar binarity in color-magnitude diagrams and luminosity functions. If, as you have quoted, 20% of Population II stars are spectroscopic binaries, the total binary frequency (extrapolating to wider separations) may be as high as 80%. Surely, if almost every Population II star were a binary, we should explore the errors of ignoring binarity!

Hesser: There are many ramifications to the increasing evidence for binaries in Population II, and I wholeheartedly agree we must explore them. Perhaps it is premature to conclude what the total binary frequency is, however. Pryor, McClure, Fletcher and I are finding that some 6% of globular cluster stars are in binaries with orbital periods between 0.2 and 20 years. This frequency appears to be significantly below that found for stars near the Sun, but it lends support to theoretical predictions that binaries will be destroyed in globular clusters by close encounters with other stars.

Pagel: A philosophical point about stellar populations: A population should be defined by a common history (*e.g.,* common effective yield) and may have a large range in kinematics and chemical composition as the halo and the bulge both do. Conversely, it is important to realize that properties of different populations may overlap, so they cannot be placed in a one-dimensional sequence. Cats and dogs may have the same age and metallicity, but they are still cats and dogs!