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# FORMATION OF THE MILKY WAY

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## ABSTRACT

We review observational evidence bearing on the formation of a prototypical large spiral galaxy, the Milky Way. New ground- and space-based studies of globular star clusters and dwarf spheroidal galaxies provide a wealth of information to constrain theories of galaxy formation. It appears likely that the Milky Way formed by an combination of rapid, dissipative collapse and mergers, but the relative contributions of these two mechanisms remain controversial. New evidence, however, indicates that initial star and star cluster formation occurred simultaneously over a volume that presently extends to twice the distance of the Magellanic Clouds.

*Key Words :* astronomy, astrophysics

## I. OVERVIEW

It is an honour to open this meeting, with its enormous range in scope from the solar system to the furthest realms by addressing a topic in which our Korean hosts are making so many important contributions. The goals of this review are to examine, however fleetingly, six themes, and thereby to impart a flavor of issues and challenges currently debated by those intrigued by how the Galaxy, and especially its halo, formed some 15 Gyrs ago. The themes are encapsulated within six whimsical questions:

1. Why should we care?
2. Are we in Jurassic Park?
3. Can you trust anyone over 10 Gyrs old?
4. Star formation by magic in the outer halo?
5. Have we got the right spices in the kimch'i?
6. Do you see that ghost?

## II. QUESTION 1

Justifiably, much of current astrophysics aims to understand the distribution of matter in the Universe and the formation of galaxies by studying high redshift objects. Many remarkable intersections of enlightenment may, however, be found between detailed studies of the Galaxy and research on even the largest scales or highest redshifts in the Universe. In turn, these intersections – some of which we will mention in this section – make the question of the formation of the Milky Way a vitally interesting subject in present-day astrophysics.

In a critical review, Fukugita, Hogan and Peebles (1996) assemble observational constraints on galaxy formation theory. In a cartoon (their Figure 5), they argue that spheroids of large galaxies were likely formed by redshift $z = 3$, and that disks were assembled at redshifts $1<z<3$, by which time most gas had turned into stars. It is interesting to consider how much this view contrasts with currently popular hierarchical merger models based upon N-body simulations (e.g., Lacey and Cole 1993, Cole and Lacey 1996), in which the halo of a large galaxy like ours is built by mergers of many sub-galactic units. Trying to understand the relative importance of mergers and dissipative collapse is a goal of many active programs on Galactic research. The debate usually compares strengths and weaknesses of Eggen, Lyden-Bell and Sandage's (1962; see also Sandage 1990) vision for Galactic formation via a rapid collapse with accompanying star and star cluster formation, and Searle and Zinn's (1978) mergers over many Gyr of smaller galaxies that have undergone independent evolution before blending into the Milky Way.

While most attempts to model galaxies assume spherical geometry for the distribution of the enigmatic dark matter, a detailed analysis (Hartwick 1994, 1996) of the spatial and kinematical properties of stellar systems in the Galactic halo suggests that they define a cigar-shaped potential. If true, how will this affect the formation and evolution of individual galaxies and of groups like the Local Group?

Today much of astronomy wrestles with the conflicting ages implied by recent measures of the cosmic distance scale and those from a comparison of globular star cluster color-magnitude diagrams (CMDs) to stellar evolution theory. Do we have a crisis in cosmology? in stellar evolution theory? in distance indicators? in all? or are the current discrepancies mere artifacts of overly optimistic error bars?

Finally, is it not fascinating that in the Galactic halo (z = 0) we find stellar systems whose chemical abundance ratios overlap with high redshift Lyman-$\alpha$ clouds (e.g., Pettini, et al. 1994), thus permitting detailed study of stars from an epoch long vanished? For these and many other reasons, study of the formation of the Milky Way remains an endeavor vitally relevant to the central physical questions of our era.

## III. QUESTION 2

Much of this review deals with globular clusters in the Milky Way halo, for which there is evidence (e.g., Richer, et al. 1996) that, with a few exceptions, they may be uniformly very old with little or no signs of an age-metallicity relation (this is a controversial subject, as the references in Richer et al. detail). But, are globular cluster systems always relics of the earliest epoch of galaxy formation, or are at least some systems actively under construction today? For instance, do multiple peaks in the color distributions (usually equated as representing peaks in the metallicity distribution function) of cluster systems around massive galaxies (e.g., Geisler, Lee & Kim 1966 for the giant elliptical, M 49) represent multiple epochs of cluster formation that, in turn, argue that most large galaxies were predominantly formed by accretion or merger processes, perhaps extending over a major fraction of their lifetime?

Another constraint on the relative epochs of star formation in large galaxies arises from the fact that globular clusters in E and dE galaxies appear to be more metal-poor than the underlying field halo stars, which suggests that most of the globular clusters formed before the halo stars (Harris 1996).

Evidence continues to build (e.g., Hilker & Kissler-Patig 1996, Holtzman, et al. 1996, and references therein) that super-starclusters forming now in galaxies undergoing major bursts of star formation (e.g., NGC 3597, NGC 6052, and NGC 7252) have luminosities and colors consistent with their being young, massive globular clusters. Even more convincing evidence is beginning to come from dynamical mass measurements: the velocity dispersions that Ho & Filippenko (1996) derive for super-starclusters in NGC 1569 and NGC 1705 are as large as expected if the clusters are analogs to globular clusters. Curiously, few such objects are found in cooling flow systems. Harris, Pritchet & McClure (1995) found no correlations between properties of the cluster systems they studied and those of cooling flows. They argue that recent cluster formation most likely results from sporadic starburst activity, and that larger cluster systems in cD galaxy halos stem from an intensive phase of cluster formation in the protogalactic epoch. Thus, some objects forming now (in heavenly 'Jurassic Parks') should fade in roughly a Hubble time to become analogs of present-day Milky Way globular clusters. It is far from clear, however, that a significant fraction of any galaxy's star cluster system comes from any but an ancient era, nor whether systems with some recent cluster formation will evolve to resemble the globular cluster system of the Milky Way today.

Taken together, the recent discoveries of young analogs for the ancient globular star clusters familiar to us all from the Milky Way's halo suggest that present-day cluster formation efficiency is low. Thus, recent cluster formation is not likely a panacea for building the populous globular cluster systems belonging to large ellipticals. Consequently, van den Bergh's (1990) longstanding concern remains, namely that it seems extremely difficult to build the populous clusters systems of large ellipticals predominantly by mergers of spirals, with their more modest cluster systems.

## IV. QUESTION 3

In this and the next section we turn to age determinations for stellar systems in the Galactic halo, which is the focus of much of our current research. Several comprehensive reviews (e.g., Bolte and Hogan 1995; VandenBerg, Stetson and Bolte 1996; Stetson, VandenBerg and Bolte 1996) are drawn upon here. There are two broad issues to address: a) how old (in absolute terms) are the oldest globular clusters, the answer to which sets a lower limit to the age of the Universe; and b) is there a range of ages among the Galactic globular clusters and, if so, what does it say about how the Milky Way formed?

Bolte and Hogan's (1995) Figure 2 summarizes well the current situation with regard to absolute ages for the most metal-deficient star clusters in the Galactic halo. Using the models of Bergbusch and VandenBerg (1992) for physical parameters thought to represent best the classical halo cluster M92 ([Fe/H]= $-2.26$, Y = 0.235, [O/Fe]= $+0.7$), and employing critically assembled values for solar-neighborhood subdwarfs, they conclude that M92 has an age of 15.8$\pm$2.1 Gyrs. Were helium diffusion included in the models, the inferred age would be $\sim$15 Gyr. If the Hubble parameter, $H_o$, is of order 70 km/sec/Mpc in a standard inflationary cosmological model with a zero cosmologial constant and $\Omega < 0.2$ (see, e.g., Carlberg, et al. 1997), then there is a $\sim 3\sigma$ discrepancy between ages inferred from globular clusters and from $H_o$ (see, for example, Figure 3 of Freedman, et al. 1994): hence, the perceived crisis in observational cosmology.

We are excited by the prospect that it now appears possible with the Hubble Space Telescope (HST) to use, for the first time, a quite different stellar chronometer to estimate globular cluster ages, and thus to provide an independent check on the traditional turnoff luminosity technique. This method compares the white dwarf luminosity functions in the nearest globular clusters, such as M4 (see Richer, et al. 1995, 1997), to theoretical white dwarf cooling curves. HST data in hand

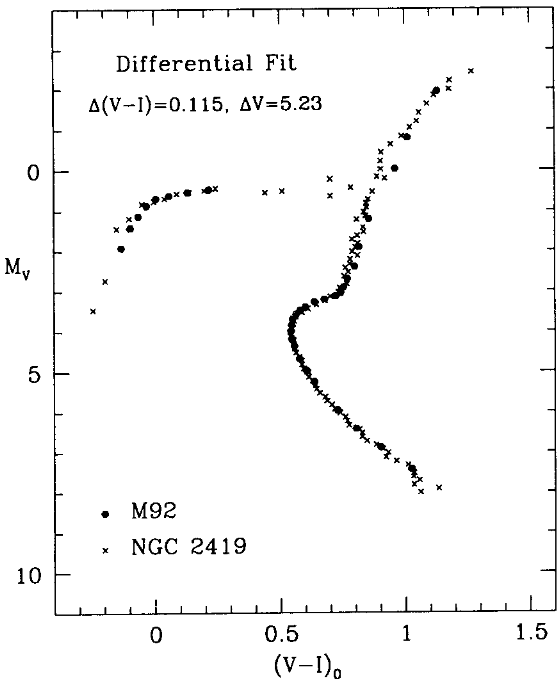


**Fig. 1.**— Comparison of the principal sequences of M92 and NGC 2419.

suggest that, if the M4 white dwarfs have carbon cores, then the faintest stars observed have ages of ~8 Gyrs, which would be incompatible with standard inflationary cosmological models for $H_o > 83$. Moreover, the inferred ages of the faintest M4 white dwarfs are already within 2 Gyrs of the oldest known disc white dwarfs in the solar neighborhood, 10.5± ~ 2 Gyrs (Oswalt, et al. 1996).

Relative ages for objects in the Galactic halo are rather easier to measure than absolute ages; nonetheless, relative ages are powerful probes of how the Galaxy might have formed. Two techniques for determining relative ages, each with strengths and weaknesses (Salaris, Chieffi & Straniero 1993), are regularly applied in the literature. (1) The luminosity difference between the horizontal branch (HB) and main-sequence turnoff (TO), $\Delta V$, and (2) the color difference, $\Delta$(color) (typically, B−V or V−I) between the TO and the base of the giant branch. Theory predicts luminosities more reliably than colors, but method (1) is operationally more difficult to apply than method (2), and suffers from uncertainties about the dependence of HB absolute magnitude on metallicity, among other things. Method (2), on the other hand, cannot be easily applied to objects with [Fe/H]> −1.0, as described by VandenBerg, Bolte & Stetson (1990) or Sarajedini & Demarque (1990).

A third method, developed by Lee, Demarque & Zinn (1994; hereinafter, LDZ), uses synthetic HB models to analyze the distribution of stars on the HBs of globular clusters. The HB phase of stellar evolution is extremely sensitive to changes so small as to be below the limits of present observational technique of essentially every parameter of which one can think (e.g., $\Delta Y$, $\Delta$[C,N,O/Fe], mass loss, core to envelope mass, etc.). Through a process of elimination, LDZ provide a scenario (see their Figure 7) in which differences in age between clusters in different regions of the halo provide a consistent picture. For example, for Galactocentric distances R< 8 kpc, LDZ's model suggests ages that are about 2 Gyrs older than for clusters with 8<R< 40 kpc, which in turn are about 2 Gyrs older than clusters with R> 40 kpc. Moreover, the inner halo appears in their picture to be more uniform in age than does the outer halo, where the puzzling 'second-parameter' effect (redder HBs than expected for the [Fe/H]) becomes more evident. [Note also that the second-parameter effect has been observed among globulars of the Fornax dSph (Smith, et al. 1996), so it is not peculiar to the Milky Way.] LDZ thus conclude from their analyses that the halo of the Galaxy was assembled in the manner envisaged by Searle & Zinn (1978) over something like one third the life of the Galaxy, with the second parameter identified predominantly with differences in age. Using method 1 on a hetrogenous data set, Chaboyer, Demarque & Sarajedini (1996) also infer age to be the second parameter. This picture's simple elegance has led to its becoming widely accepted. While no doubt age differences between halo clusters is part of the answer, recent careful differential comparisons suggest that Nature may not yet have fully revealed her secrets to us.

For instance, Stetson (1995) reported highly accurate differential photometry (same night, telescope, detector, analysis, etc.) for the canonical Northern hemisphere second-parameter pair, M3 and M13. From the CMDs in the TO and subgiant regions, he finds that M13 can be at most 0.5 Gyr older than M3 and/or M13 is 0.5 dex more metal poor than M3. However, from high-dispersion spectroscopy, Kraft et al. (1993) find that the two clusters have the same [Fe/H] to within ±0.04 dex, while the synthetic HB studies implied they differ in ages by more than 2.5 Gyr. Because there is evidence for deep mixing in M13 in the form of six first-ascent giants that are very deficient in oxygen, Kraft et al. speculate that perhaps stellar angular momentum is regulating the mixing and driving the HB morphology, rather than differences in ages.

We have been using the Hubble Space Telescope (HST) in Cycles 4-6 to make V,I CMDs for objects in the outer halo of the Galaxy. Our goals include absolute and relative age determinations that we hope will illuminate the formation scenario for the Milky Way. Most of the clusters in the outer halo have red HBs and are of low luminosity. An exception is NGC 2419, a luminous, blue HB cluster located at $R_{gc}$=95 Kpc (i.e., nearly twice the distance of the Large Magellanic Cloud). NGC 2419 has the same [Fe/H] as the inner halo cluster, M92. From $M_V = +8$ to $-2$ the two CMDs are indistinguishable (see Figure 1). In turn, this suggests that these two clusters represent an initial burst of star cluster formation that extended over a huge volume of the proto-Galaxy. In view of the fact (VandenBerg, Bolte and Stetson 1990) that all the most metal-deficient halo clusters for which accurate relative ages are available have the same age to within ~0.5 Gyr, including now NGC 2419 at nearly twice the distance of the Magellanic Clouds in the far halo, we have a powerful constraint on the spatial extent of the initial cluster formation epoch.

However, interpretation of preliminary HST data for Pal 4, another far halo object which is thought to be a strong second-parameter cluster, has proven problematical. Available metallicity determinations span a wide range, which makes it difficult to select an appropriate well studied inner halo cluster for differential comparison with Pal 4. If we choose M5 for that purpose, initial results would suggest that Pal 4 is some 5 Gyrs younger via the $\Delta$color technique and about 1.5 Gyrs younger via the $\Delta V$ technique. If the two clusters have the same [Fe/H] but there were a dramatically different ratio of $[\alpha/\mathrm{Fe}]$ in them, that might explain the discrepant relative ages inferred by the two techniques. We are also concerned that the Pal 4 reductions of data spanning two cycles may still have some small photometric calibration error.

In summary, from the study of globular star clusters in the outer halo, several important conclusions hold. New HST results suggest that the initial burst of star cluster formation was a global, rapid phenomenon that occurred over a huge volume. The absolute ages of these oldest, metal-deficient clusters, 15±2 Gyr, conflict with most recent determinations of $H_o \sim 70$. While at all $R_{gc}$ and at most metallicities there definitely are a handful of globular clusters that appear younger by a few Gyr than the bulk of the system, much recently accumulated evidence suggests that age as the dominant second parameter remains open to debate.

## V. QUESTION 4

It has been clear since the late 1970s and the work of Zinn, Searle and Zinn, Aaronson and Mould, and others that the other bound stellar systems in the outer halo, the dwarf spheroidal (dSph) galaxies, contain more than one generation of stars. Their great distances have made quantitative analysis slow going, but recent work offers dramatic insight into the objects that some consider to be possible building blocks for the Milky Way halo.

As shown in Figure 2, deep photometry from the CTIO 4-m telescope by Smecker-Hane, et al. (1994, 1997) for the Carina dSph reveals evidence for four distinct episodes of star formation. Efforts by Smecker-Hane to create synthetic CMDs for Carina suggest that some 2% of the mass is represented by star formation

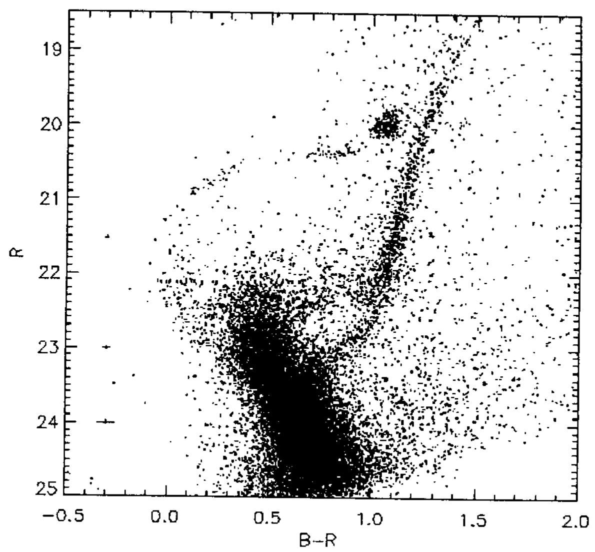


**Fig. 2.**— A CMD for the Carina dwarf spheroidal galaxy (Smecker-Hane et al. 1997).

that ocurred 1 to 1.5 Gyr ago, 28% of the mass by star formation that ocurred from 2.5 to 3.5 Gyr ago, 50% of the mass by star formation about 3.5 to 7 Gyr ago, and the remaining 20% of the mass by star formation about 10 to 14 Gyr ago. Amazingly, there is very little evidence for chemical enrichment in excess of ~0.2-0.3 dex; it would appear that galactic winds must have let most of the newly synthesized metals escape during the major star formation epoch ~6 Gyr ago while leaving a significant fraction of the gas behind. The long hiatus between the initial and subsequent bursts of star formation is puzzling; why wouldn't there have been star formation driven by a recollapse on a cooling time scale of some 100 Myrs?

Aaronson and Mould's (1980) discovery of carbon stars in the much more luminous ($M_V = -14$) dSph, Fornax, strongly hinted at an intermediate age population. Fornax has five globular clusters, which makes it unique among the classical outer-halo dSphs. Buonanno, et al. (1985) provided evidence for a large range in metallicities in Fornax, $-2.2 < [\mathrm{Fe/H}] < -0.7$. CCD photometry from Dec. 1995 with the CTIO 1.5-m telescope by Stetson, Hesser and Smecker-Hane (1997; see Stetson 1996) covers a large portion of Fornax and reveals several interesting properties. Star formation appears to have been remarkably steady until about 4 Gyr ago, when it dropped dramatically; nonetheless, there is a smattering of stars only a few 100 Myrs old (see also Beauchamp, et al. 1995)! The red-giant and horizontal branches show clearly the effects of metallicity evolution. In contradistinction to Carina, it is clear that Fornax has undergone a complex evolution in age and metallicity.

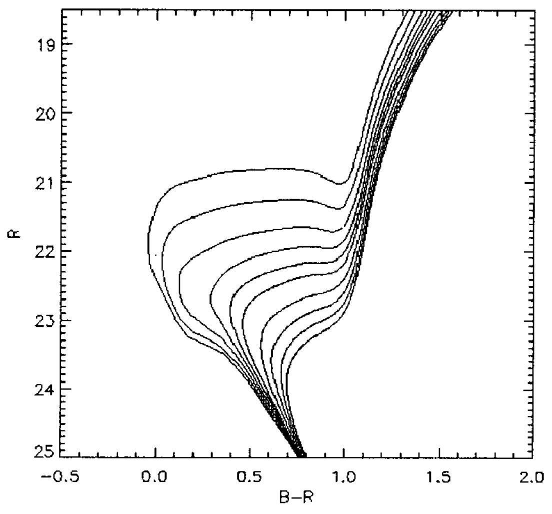


**Fig. 3.**— New theoretical isochrones for [Fe/H]= −1.84 from (VandenBerg et al. 1997). For comparison with the Carina dSph CMD, ages 1.3, 2, 3, 4, 5, 6, 8, 10, 12, 14 Gyr are shown.

Mighell & Rich (1996) used HST to image the Leo II dSph, from which they infer a ±0.25 dex range in [Fe/H] and a dominant stellar population of age 9±1 Gyr, although they note that the CMD definitely shows a range of ages from 7 to 14 Gyr. CFHT and KPNO 4-m photometry of the Draco dSph (Stetson 1996) reveals yet another distinct CMD, which this time appears to be dominated by a single old population with a modest percentage of younger and/or peculiar stars. Thus, the situation with dSphs is reminiscent of planetary satellites in the solar system: just as Voyager images revealed each satellite to be unique and the system to possess an unimagined rich spectrum of characteristics, deep CMDs for the dSphs reveals them to be unique and their system to be rich with clues to star formation processes in low-mass galaxies.

When, as in the previous section, we focus attention upon the globular star clusters in the Galactic halo, we develop a quite restricted sense of the stellar populations there. The globulars, which represent only some 2% of the luminous mass in the halo, generally exhibit a modest range, if any, in age from one cluster to another, and no detectable range within a given cluster. On the other hand, dSphs, whose radial distribution overlaps with the outermost globulars of the Galaxy, exhibit episodic star formation, that, in the apparent absence of gas (Knapp, Kerr & Bowers 1978), is as if by magic. [Note: the latter HI observations definitely deserve repeating, because then poorly-known radial velocities were used to determine the scanning range; the resulting limits could be greatly improved.] Carina and Fornax offer dramatially contrasting situations. Carina exhibits a large age spread arising from distinct star formation episodes and a small [Fe/H] range, while Fornax exhibits a large age spread, almost continous star formation, and a large spread in [Fe/H]. Spectra are needed for large samples of stars if we are to disentangle age and metallicity degeneracies in the dSphs, and if we want to learn how the gas content evolved with time (i.e., inflow vs outflow). The dSphs have much to each us about how star formation is regulated, and how chemical elements evolve in young, proto-Galactic fragments and also in low metallicity quasar absorption line systems.

## VI. QUESTION 5

Age determinations for globular clusters, with their fascinating implications for cosmology and the chronology of the formation of the Galaxy, require knowledge of the abundances of the objects being dated. However, the uncertainties underlying our knowledge of halo abundances are perhaps not stressed enough in our reach for answers to the big questions. Space does not allow treatment of this topic in detail, and the reader is referred elsewhere for reviews (e.g., Briley et al. 1994, Hesser 1996). For instance, it is widely recognized that in the halo, $\alpha$-elements are enhanced relative to the Fe-peak elements, such that $[\alpha/\mathrm{Fe}] \sim +0.4$ for $[\mathrm{Fe/H}] < -0.5$. Such trends presumably reflect the difference in the integrated amount of chemicals produced from SNe I and II at different times. Similarly, the relative ratios of C, N & O vary from cluster to cluster and from star to star within individual clusters. With present technology, abundance determinations at spectral resolution above 40,000 (as required, for instance, to measure [O/Fe]) are limited to the most luminous giants, whose C, N & O behavior argues that they have undergone deep mixing as they ascended the giant branch (see, e.g., Briley et al. 1994). If the surface abundances have been affected by dredge-up from the interior, what values should be used for the age-sensitive turnoff from the main sequence when comparing isochrones to observed CMDs?

In the past few years, measurements of the infrared triplet of Ca II have become synonomous with 'metallicity' in many studies. Extensive measurements of the Ca index for globular cluster giants (Rutledge et al. 1997a,b) found tight correlations with the widely used Zinn & West (1984) [Fe/H] scale based generally on integrated light and/or low-dispersion spectroscopy, as well as with a scale based on sytematic analysis of equivalent widths from high-dispersion spectra (Carreta & Gratton 1996). However, the latter authors demonstrate a significant non-linear relationship beween their metallicity scale and that of Zinn & West. While there is no doubt that the Ca index is a powerful probe of halo chemistry, it is perhaps not entirely clear to what extent it reveals differences in $\alpha$ elements from cluster to cluster, differences in [Fe/H] from cluster to cluster, or differences in Galactic formation physics.

The challenges of making accurate measurements, and of then interpreting them correctly through model atmospheres to deduce the chemistry of stellar systems in the halo, leave open the nagging possibility that perhaps we don't know their chemistry well enough to establish definitive ages and an age profile for them. Conceivably some of the answers to the fundamental questions of Galaxy formation and cosmology addressed earlier are more compromised than we yet appreciate. Moreover, to achieve a full understanding of the halo, we will need to understand how the field and halo cluster stars came to have different metallicity distribution functions (e.g., Suntzeff, et al. 1991, Laird, et al., 1993, Carney, et al. 1996) and we will need accurate abundances for the heavily reddened globulars in the innermost regions of the Galaxy. Just as in making good kimch'i, we need to get the chemistry right for the Galactic halo if we are to have confidence in our derived properties...and we may have a greater distance to go towards that goal than we'd like to believe.

## VII. QUESTION 6

Efforts to unravel the history of the formation of the Galaxy rely heavily upon the stellar systems in the halo, yet, as noted earlier, the globular clusters represent only some 2% of the luminous mass in the halo. A long standing question has been what fraction of the halo field stars originated in globulars or other stellar systems that might have dissolved due to Galactic tidal or other forces. A closely related question is what fraction of halo dark matter might be baryonic in the form of extremely low mass stars. As with the previous section, the dynamical state and evolution of halo objects is a vast subject, from which only a few salient points resulting from recent studies can be made here.

Ground-based studies to faint limiting magnitudes for nearby globular clusters raised the tantalizing possibility that the luminosity function in some clusters continues to rise for $M_I > 8$ (e.g., Richer et al. 1991). However, HST photometry by Paresce et al. 1995 and Richer et al. 1995 reveals a turnover in the luminosity function, such that it now seems less likely that present-day clusters harbor a wealth of potential dark matter for contribution to the Galactic halo through evaporation. Analyses of star counts in the Hubble Deep Field (e.g. Méndez et al. 1996) find, as do the cited globular cluster studies, that the halo luminosity function is smaller than what would be projected by extrapolation of the disc luminosity function in the solar neighborhood. Other indicators (e.g. Mould 1996; Alcock et al. 1997) also support a turnover in the main-sequence luminosity function of the halo.

For a number of years, there has been considerable theoretical debate regarding how much of the original globular cluster population in the Galaxy has been destroyed by dynamical friction, disc shocking and evaporation. Recently there has been convergence on the view that a substantial fraction of the original cluster population in our Galaxy and in others has likely been dissipated by these processes, which act with differing efficiencies depending upon the mass, concentration, location and orbital parameters of individual clusters (e.g., Okazaki & Tosa 1995, Capriotti & Hawley 1996, Gnedin & Ostriker 1997). Moreover, it is argued that over very long times these processes could transform cluster systems with power-law luminosity functions and young, massive clusters (like those found in the Magellanic Clouds) into systems of old clusters with Gaussian luminosity functions and other similar systemic properties as observed for many galaxies (e.g. Harris 1991).

From the perspective of trying to understand the balance between dissipative collapse of gas and accretion of previously formed stellar systems in the formation of the Milky Way and other large galaxies, the discovery of the dissolving Sagittarius dSph (Ibata, Gilmore & Irwin 1994) provides reassurance (as if any were needed!) that mergers occur. On the other hand, Unavane, Wyse & Gilmore (1996) use chemical properties of the dSphs to place upper limits on the number of Carina and Fornax dSphs that could have been accreted by the Milky Way in the past 10 Gyrs. They argue, based upon the colour distribution and metallicities of their stars compared with field halo stars, that fewer than 60 Carina-like and fewer than six Fornax-like dSphs could have been accreted in the past 10 Gyrs. However, potential complications in an analysis like theirs may revolve around the balance between Galactocentric distance (e.g., stripping of gas from a dSph) and internal physical processes as regulators of star formation history.

Theoretical ideas, from Toomre & Toomre (1972) to the present, about the role of dynamical merging in galaxy formation are summarized by Lynden-Bell & Lynden-Bell (1995), whose new analysis of positions and velocities for globulars and dSphs identifies numerous possible ghostly streams in the halo that may mark orbits of ancestral satellites that merged into the Milky Way. Johnston, Hernquist & Bolte (1996) have also demonstrated new analysis techniques that suggest 'debris from minor mergers can remain aligned along great circles throughout the lifetime of the Galaxy,' while Majewski, Munn & Hawley (1996) used a north Galactic pole proper motion survey to argue that the halo is not dynamically mixed. Bellazzini, et al. (1996) suggest that inner halo GCs experienced a different, much more chaotic dynamical evolution from that of disc GCs, even though the radial zone the two groups occupy is nearly the same. Minniti's (1996) kinematic study of bulge red giants strengthens the conclusion that the Galactic bulge formed via dissipative collapse from material remaining after halo formation; among his predictions is that the metal-rich bulge clusters should not be older than the metal-poor halo clusters.

In brief, then, the topic of 'ghosts' in the Galactic halo touches upon such fundamental issues as the role of baryonic material in dark matter and the history

Galactic formation. Recent discoveries of a turnover in deep GC luminosity functions appears to diminish the likelihood that evaporation of extremely faint stars from present GCs contributes in a major way to halo dark matter. That notwithstanding, there has been convergence recently in favor of the idea that the observed GCs are likely a small fraction of the original population, such that a high percentage of halo field stars might have originated in now-dissipated GCs. Color and metallicity properties of field halo stars limit to relatively few the number of dSphs that can have been accreted in the last 10 Gyrs. New analytical techniques and models provide hope that ethereal signatures of past merger events can be mapped, and thus that we may eventually be able to constrain the relative importance of dissipative collapse and mergers in Galactic halo formation.

## VIII. SUMMARY

Unavoidably a brief review that attempts to highlight major research themes for a diverse audience leaves out much and risks not conveying the excitement and controversies of a subject as vast of the formation of the Milky Way. Readers wishing to explore more will find thorough reviews and additional references in, e.g., van der Kruit & Gilmore (1996), Blitz & Teuben (1996), Morrison & Sarajedini (1996) and van den Bergh (1996).

To summarize the theme of this review, the collective evidence presently favors the view that the Milky Way likely formed by a combination of rapid, dissipative collapse (which may have been particularly dominant in the inner regions) and mergers with stellar systems such as dSphs and dIrrs (which may have been particularly dominant in the outer regions). The balance between these processes is a matter of intense current research and controversy. An important constraint stemming from recent ground-based and HST-based studies is that the GCs most deficient in heavy elements exhibit a range of ages $< 0.5$ Gyrs, whether located in the far outer halo or the inner halo. That is, initial star and star cluster formation appear to have occurred simultaneously over a huge volume. Such a remarkable observation seems worthy of careful contemplation over *kimch'i* and *soju* outside this beautiful lecture theatre.

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