Formation of the Galactic Halo .... Inside and Out
ASP Conference Series, Vol. 92, 1996
Heather Morrison and Ata Sarajedini, eds.

Globular Clusters as Fossils of Galaxy Formation

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Abstract.

The globular clusters in the halos of large galaxies like our own are almost certainly fossil remnants of the early star-forming subsystems from which these galaxies were built. The ages of the halo clusters in our Galaxy indicate a prolonged period of galaxy building lasting at least several Gyr, and their masses indicate that they were formed in very massive star-forming complexes in protogalactic subsystems that may have resembled the present 'blue compact dwarf' galaxies. The surviving descendants of these subsystems are probably among the present dwarf spheroidal or nucleated dwarf galaxies, and the recently discovered Sagittarius dwarf is probably an example of such an object just now being accreted by our Galaxy and depositing into its halo four globular clusters including the second most luminous one in our Galaxy, M54.

1. Introduction: What Can the Globular Clusters Tell Us?

As the oldest known subunits of our Galaxy, the globular clusters are our primary fossils from its early evolution, and they may hold the key to understanding its formation. What kinds of information might they provide about galaxy formation? To help focus this question, it will be useful to recall the major scenarios that have been proposed for the origin of the globular clusters. Two broad types of possibilities have been considered: one is that the globular clusters were the first condensed systems to form in the early universe, and the second is that they originated in larger star-forming systems that later merged to form the present galaxies. The first possibility includes the suggestion of Peebles & Dicke (1968) that the globular clusters were formed by Jeans fragmentation in the early universe, and the suggestion of Fall & Rees (1985, 1988) that they were formed by thermal instability in early hot gaseous halos. The Fall & Rees hypothesis has been popular among theorists who have used it to predict the characteristic properties of globular clusters, although it has proven difficult to justify the assumed thermal behavior of the cluster-forming gas clouds (Palla & Zinnecker 1988). The second type of scenario has in any case gained increasing attention in recent years, partly because it is more consistent with current cosmological models which predict that cosmic structures including galaxies are built up by the bottom-up merging of smaller units into larger ones (for reviews, see Larson 1990b, 1992b). In the first type of scenario, the globular clusters might tell us something about fragmentation processes in the early universe, while in the bottom-up picture of galaxy formation, the globular clusters might actually represent the densest surviving parts or 'bones' of the early subsystems that merged to form the present galaxies, and they might then tell us something about the chronology of the galaxy building process and something about the nature of the primitive galactic building blocks.

Galaxies are observed to be clustered hierarchically, and they are also distributed in a network of filaments and cellular structures on a wide range of scales (Maddox et al. 1990; de Lapparent, Geller, & Huchra 1991; Giovanelli & Haynes 1991); clearly, any adequate understanding of their origin must account for these clustering characteristics. Numerical simulations of the growth of structure in a dark-matter-dominated universe have successfully reproduced the basic clustering properties of galaxies by postulating an initial spectrum of density fluctuations that is approximately a scale-free power law on the relevant range of scales; since these density fluctuations have their largest amplitudes on the smallest scales, small systems tend to form first and larger ones are then built up by the progressive merging of smaller structures into larger ones (Frenk et al. 1988; Zurek, Quinn, & Salmon 1988; Carlberg & Couchman 1989; White & Frenk 1991; Evrard, Summers, & Davis 1994). In a high-density universe, such mergers are predicted to continue at a significant rate up to the present time and beyond. Simulations that include the physics of the gas show that the gas condenses strongly at the centers of the dark-matter 'halos' that form, and that if the feedback effects of star formation are not included, the gas becomes highly clumped and loses much of its angular momentum to the dark matter, becoming much more centrally concentrated than in real galaxies (Navarro & Benz 1991; Navarro & White 1994). Moreover, too many small objects are formed for the results to be consistent with the observed galaxy luminosity function (White & Frenk 1991; Cole 1991; Cole et al. 1994). Efforts are under way by several groups to produce more realistic simulations that properly include the effects of star formation, but the existing results suggest that the first star formation may occur in gas that has become highly condensed at the centers of the first dark-matter halos to form; even though such systems may not closely resemble most present-day galaxies, they may still be of interest as the possible birth sites of globular clusters, as will be discussed further below.

The most realistic simulations of the formation of a spiral galaxy like our own have been made by Katz (1992) and Steinmetz & Müller (1994, 1995), who have simulated the evolution of a spherical galaxy-sized piece of a standard 'cold dark matter' universe which is arbitrarily given the appropriate amount of angular momentum. The results show an initial chaotic stage during which mergers between clumps build up a dark halo and a stellar spheroid, followed by a period during which the remaining gas organizes itself into a disk. During the initial chaotic stage several small satellites are formed by the condensation of gas in peripheral dark-matter clumps, and these satellites may survive for a few orbits before being disrupted and merged into the forming galaxy. It is plausible that such small satellites could be the birth sites of globular clusters, as in the hypothesis of Searle (1977) and Searle & Zinn (1978) that the globular clusters in the outer halo of our Galaxy were formed in protogalactic 'fragments' which survived for a time as independent star-forming systems before being merged to build up the halo (see also Larson 1988, 1990b, 1992b; Freeman 1990, 1993, 1996).

2. Globular Clusters and Galactic Chronology

If the globular clusters in the Galactic halo were formed in protogalactic fragments or satellite systems that were later merged to build the halo, the ages of these clusters might provide some information about the chronology of the galaxy building process. However, the cluster ages themselves do not necessarily directly record the merger history of the halo, since the halo clusters could have been formed in satellite systems long before these satellites were merged into the halo. Thus, the discovery of very old clusters in the Galactic halo would not strongly constrain possible merger histories, but the discovery of relatively young halo clusters would be a more significant finding because the progenitor systems of these young clusters could only have been disrupted and merged with the halo after the clusters had formed, and such mergers could have occurred relatively recently in Galactic history.

In several earlier reviews of globular cluster chronology, it was concluded that the globular clusters in our Galaxy are not all coeval and that age differences of several Gyr exist in at least a few well-studied cases (e.g., Larson 1990a, 1992b). This conclusion still appears to be valid, and it is supported by the most recent discussion of this subject by Chaboyer, Demarque, & Sarajedini (1996), which is based on new age estimates for 43 globular clusters. Although the uncertainties remain too large for strong statements to be made about age differences in most individual cases, Chaboyer et al. (1996) argue that the sample of clusters studied has a statistically significant age spread of at least 5 Gyr, and that some of the age differences are much larger than their uncertainties. These results also support Zinn's (1993) division of the halo clusters into two age groups on the basis of horizontal-branch morphology, since they show that Zinn's 'younger halo' group has a significantly smaller average age than his 'old halo' group by about 2 to 3 Gyr. Since the younger group has a larger average distance from the Galactic center, this finding also supports the suggestion of Searle & Zinn (1978) that the outer halo is on the average a few Gyr younger than the inner halo. The most striking feature of the age distribution of the Galactic globular clusters, which has now been known for some years and is not disputed by any researchers in the field, is that the outer Galactic halo contains a group of mostly relatively small clusters including Pal 12, Rup 106, Arp 2, and Ter 7 whose ages of the order of 10 to 12 Gyr make them substantially younger than the bulk of the halo clusters.

These results suggest that the halo of our Galaxy was built up over a period of at least a few Gyr, perhaps by an inside-out accretion process, and that this process continued at least until the youngest outer halo clusters were formed perhaps 10 Gyr ago. The fact that the oldest stars and clusters in the local Galactic disk are about as old as the youngest halo clusters suggests that the local thin disk may have formed only after cluster formation in the halo was completed (Larson 1990a,b, 1992b). Although our Galaxy has evidently not experienced any further major accretion events capable of disrupting the disk, it is possible that minor accretion events affecting only the halo and not the disk have continued to occur (Navarro, Frenk, & White 1994); indeed, several contributors to this meeting have already noted that our Galaxy is apparently just now accreting the recently discovered Sagittarius dwarf galaxy, which contains four already known outer-halo globular clusters including Arp 2 and Ter 7 (see

Section 6). This discovery illustrates the fact that, even though the formation of the Galactic globular clusters may have ceased about 10 Gyr ago, the merging of the cluster-forming subsystems into the halo could have continued until much more recently, and even up to the present time.

3. Lifetimes and Luminosity Functions: Are the Globular Clusters Special?

What can we say about the nature of the cluster-forming protogalactic fragments or satellite systems from which the Galactic halo was built? Clearly, these systems must have been capable of forming clusters much more massive than the smaller open clusters that have formed more recently in the disks of our Galaxy and other spiral galaxies. Did this require a special cluster formation mechanism that was qualitatively different from the processes that have occurred more recently in our Galaxy and others, or was only a quantitative difference in the scale of cluster formation processes required?

An important related question is whether the globular clusters are a unique class of objects that differ in some fundamental way from the open clusters, or whether there is a continuity in properties between globular clusters and open clusters, whose formation can be studied directly at the present time. A difference that has sometimes been emphasized is that the luminosity function of the globular clusters is sharply peaked and narrower than the luminosity function of the open clusters, which is not peaked but increases monotonically toward smaller luminosities (Harris 1993; van den Bergh 1993). Many authors have assumed, following Fall & Rees (1985, 1988), that the peaked luminosity function of the globular clusters requires a special formation mechanism that produces objects with a preferred mass. However, the fact that the globular clusters have a peaked luminosity function at the present time does not necessarily imply that they were *formed* with such a peaked luminosity function, since any clusters that might initially have been formed with masses much smaller than those of the observed clusters would have had shorter lifetimes and so might not have survived to the present time; the present peaked luminosity function could then have resulted just from cluster destruction processes.

The most important destruction process for most globular clusters is evaporation due to two-body relaxation (Aguilar, Hut, & Ostriker 1988), and the most realistic models of cluster evolution predict that a cluster evaporates completely after about 20 half-mass relaxation times (Spitzer 1987; Larson 1992a). The half-mass relaxation time is given approximately by 0.01 times the number of stars in the cluster times the crossing time at the half-mass radius, and the median value of this relaxation time for the observed globular clusters in our Galaxy is about 1 Gyr. The median evaporation time of these clusters is therefore predicted to be about 20 Gyr, which is comparable to the Hubble time and also to the typical ages of these clusters. Since the relaxation time is proportional to the cluster mass for a given half-mass density, the predicted evaporation times are generally shorter for the less massive clusters. The fact that the median cluster lifetime is comparable to the Hubble time is therefore almost certainly not an accident, but suggests that many clusters that were initially formed with smaller masses and shorter lifetimes have since disappeared, leaving only those clusters that had sufficiently large masses and long lifetimes to survive to the present (Surdin 1979; Larson 1988, 1992a). The surviving clusters would then have a peaked luminosity function even if cluster formation processes in the Galactic halo had initially produced objects with a mass function increasing monotonically toward smaller masses, like the mass function of the open clusters.

More detailed treatments of cluster mortality that include other destruction processes have been given by Aguilar et al. (1988), Surdin (1979, 1993, 1996), and at this meeting by Capriotti, Hawley, & Hamlin (1996) and Murali & Weinberg (1996). The basic conclusion of all of these studies is that the luminosity function and other statistical properties of the globular clusters in our Galaxy have been strongly modified by cluster destruction processes, and that the observed distributions can be accounted for to a large extent as a consequence of these destruction processes, without requiring the clusters to have been formed with any special properties. Therefore, the peaked luminosity function and the other statistical properties of the globular clusters in our Galaxy do not strongly constrain theories of their formation.

Several authors have noted that the mass functions of the globular clusters in our Galaxy and other galaxies can be approximated for masses larger than about $10^5\,M_\odot$ by a declining power-law function of mass, the best-fitting exponent in such a power-law approximation for the number of clusters per unit mass interval being between -1.5 and -2.0 (Surdin 1979, 1996; Harris & Pudritz 1994; McLaughlin & Pudritz 1996; Harris 1996). Most of the clusters whose masses are larger than $10^5\,M_\odot$ have lifetimes longer than the Hubble time, and therefore this power-law form for their mass function may approximately reflect the distribution of masses with which they were formed. It is also similar to the mass functions found for both the open clusters and the dense molecular clumps in which they are born, and this common power-law form can be understood theoretically as being produced by clump coagulation processes like those that have probably built up the more massive cluster-forming clumps (Harris & Pudritz 1994; McLaughlin & Pudritz 1996). This similarity in the initial mass functions suggests that the globular clusters may have been formed by processes similar to those that presently form open clusters, differing mainly in scale as suggested by Larson (1988, 1993). This idea has been developed further by Harris & Pudritz (1994) and by McLaughlin & Pudritz (1996), who have proposed that the globular clusters were formed in 'supergiant molecular clouds' present in the early Galactic halo. If these 'supergiant clouds' actually belonged to protogalactic subsystems or satellites, this hypothesis would be consistent with the hierarchical picture of galaxy formation discussed above, and it would provide a possible connection between the early formation of globular clusters and the present-day formation of open clusters.

4. Observations of Present-Day Cluster Formation

If there is no real dichotomy between globular clusters and open clusters but rather a continuity of properties and perhaps of formation processes as suggested above, then it is of interest to examine the whole range of scales of cluster formation that can be observed at the present time, and to see what trends may appear when we look at larger and larger mass scales. An obvious question will be whether we can, or even need to, extrapolate from these observations to infer something about the circumstances required for the formation of clusters as massive as typical globular clusters. A review of this subject has been given previously by Larson (1993), so only a summary will be presented here.

An important recent advance in our understanding of star formation has been the realization that nearly all stars are formed in groups or clusters of some kind. Even in the nearby Taurus-Auriga region, which has been regarded as prototypical of 'isolated' star formation, the T Tauri stars are actually mostly distributed in a hierarchy of small groups of various sizes (Larson 1982; Gomez et al. 1993). In a second nearby region of star formation associated with the ρ Ophiuchi cloud, most of the newly formed stars are located in a single compact cluster embedded in the dense core of this cloud, and this cluster has been much studied as a possible newly formed open cluster (Wilking, Lada, & Young 1989; Wilking 1992). In the most prominent visible region of star formation, the more distant and massive Orion complex, both the Orion A and B giant molecular clouds contain larger embedded clusters of newly formed stars; most of these clusters may soon be dispersed when their parent clouds are destroyed, but some may survive cloud destruction as bound open clusters, the best candidate being the relatively massive and condensed Trapezium cluster in the Orion A cloud (Zinnecker, McCaughrean, & Wilking 1993). The Orion B cloud contains several similar but smaller clusters (Lada 1992; Lada, Strom, & Myers 1993), and the embedded clusters in the Orion A and B clouds together account for most of the newly formed stars in the Orion region and most of the newly formed stars within 500 parsecs of the Sun. Therefore these clusters appear to be representative of the environments in which most stars are currently forming in the local Galactic disk.

More massive young clusters are found in the Large Magellanic Cloud, which is a rich hunting ground for students of star formation and contains many clusters and stellar aggregates of all descriptions, some of which may have been formed by triggering mechanisms (Bruhweiler, Fitzurka, & Gull 1991; Elmegreen 1992; Larson 1993). Some of the young LMC clusters are more massive than any found in our Galaxy, and they include the most luminous young cluster in the entire Local Group, NGC 2070 at the center of the giant 30 Doradus H II region. It has recently become possible to study this cluster in some detail with the Hubble Space Telescope, and the results show it to be a symmetrical, highly centrally concentrated, globular-like cluster with a normal stellar mass function down to the smallest masses that can be studied, and with its most massive stars most strongly concentrated toward the center (Hunter et al. 1995). All of these characteristics are very similar to those of the Trapezium cluster, but NGC 2070 is two orders of magnitude more massive and has properties consistent with those that would be expected for a young globular cluster with a mass of a few times $10^4\,M_\odot$ (Hunter et al. 1995). Thus, this object is of great interest as the nearest possible prototype of a newly formed small globular cluster. It is noteworthy also that the 30 Doradus star-forming complex is itself unique in being the largest such complex in the entire Local Group, containing about $10^8\,M_\odot$ of gas and a number of other young clusters in addition to NGC 2070 in a region about 2 kpc across at the end of the LMC bar (Bruhweiler et al. 1991; Larson 1993).

Even more massive clusters are apparently formed in starburst galaxies, especially in merging systems, and this possibility has been of considerable interest because such a process might help to account for the high frequency of globular clusters in elliptical galaxies, if these galaxies are indeed formed by mergers (Schweizer 1992). Several merging or recently merged systems have been observed with the Hubble Space Telescope, including NGC 1275 (Holtzman et al. 1992), NGC 7252 (Whitmore et al. 1993), NGC 4038/4039 (Whitmore & Schweizer 1995), and NGC 3690 (Meurer et al. 1996), and all have been found to contain extremely luminous young stellar aggregates whose sizes and estimated masses overlap with those of the globular clusters; their luminosity functions also have a power-law form similar to that of the open clusters and the more massive globular clusters. These properties therefore suggest that some of these luminous young stellar aggregates, especially the more compact and massive ones, will evolve into clusters resembling globular clusters after a Hubble time; the surviving clusters may have a peaked luminosity function if the less massive ones evaporate within this time, as discussed in Section 3. Thus it is possible that mergers of large disk systems and the accompanying formation of very massive clusters might contribute to the formation of elliptical galaxies and their extensive globular cluster systems.

However, it does not seem likely that *most* of the known globular clusters were formed in this way, since most globular clusters are older than most disks. Also, in the case of our Galaxy, the fact that the entire Galactic halo has a relatively small stellar mass means that it cannot have been formed by the merging of any sizable disk systems. If the clusters in the halo were actually formed in protogalactic fragments or satellites before these systems were disrupted and merged into the halo, then mergers could presumably not have played any important role in the formation of these clusters. A more promising empirical model for the formation of the halo globular clusters may be provided by certain 'blue compact dwarf' starburst galaxies such as NGC 1705, which has near its center a young 'super star cluster' with a mass larger than $10^6\,M_\odot$ and a half-mass radius of about 1 parsec, which is thus a strong candidate for a young globular cluster (Meurer et al. 1992, 1996). Like NGC 2070 in the 30 Doradus nebula, this cluster is located at the center of a giant filamentary H II region, and it is part of a large star-forming complex that contains about $10^8\,M_\odot$ of gas and several other young clusters in a region about 1 kpc across (Meurer et al. 1992). In this galaxy, there is no obvious dynamical phenomenon such as a bar or tidal interaction to account for the presence of such a large gas concentration near its center, but another effect that may be of general importance in dwarf galaxies is that they are dominated by dark matter whose gravitational field may play a role in causing gas to condense at their centers (Larson 1992b, 1993). If this leads to the formation of massive globular clusters, then blue compact dwarfs like NGC 1705 may be the closest present-day counterparts of the 'Searle-Zinn fragments' in which the globular clusters in the Galactic halo were formed.

In summary, it appears that the formation of star clusters at the present time occurs in a qualitatively similar way on a wide range of scales, larger clusters forming in larger star-forming complexes with a ratio of cluster mass to total gas mass between about 10^{-3} and 10^{-2} (Larson 1988, 1993). The formation of clusters as massive as typical globular clusters apparently requires very massive complexes containing at least $10^8\,M_\odot$ of gas in a kiloparsec-sized region. Such massive gas concentrations are not presently observed in our Galaxy or most normal spiral galaxies, although the required conditions may be approached in regions such as the 30 Doradus complex at the end of the LMC bar. Conditions sufficiently extreme to form globular clusters are apparently found at present only in the relatively rare starburst galaxies, among which the blue compact dwarfs may be the closest analogs of the protogalactic subsystems in which the halo clusters of our Galaxy were formed (Larson 1988, 1993; Meurer et al. 1996).

5. Why Were Globular Clusters Formed Only at Early Times?

If, as suggested above, the formation of globular clusters requires more massive star-forming complexes than are presently seen in most galaxies, then such massive complexes must have much more abundant at early times. In particular, if the globular clusters in the halo of our Galaxy and other galaxies were formed in protogalactic subsystems resembling compact dwarf galaxies with large gas concentrations like NGC 1705, such compact systems must have existed in large numbers during the early stages of galaxy formation. Why should the formation of such systems have been strongly favored at early times, and why have they become relatively rare by now?

Part of the answer is probably the fact that the first systems to condense in the early universe had no angular momentum initially, since all of their matter had emerged from the same infinitesimal volume of space; angular momentum was generated only later by tidal torques. Therefore the first protogalactic subsystems would have had little angular momentum, and this would have allowed their gas to become highly condensed. The 'Searle-Zinn fragments' may have originated during this early stage of galaxy formation before much angular momentum had been generated by tidal torques, and the formation of very massive clusters in them may have been favored by the condensation of low-angular-momentum gas at their centers. At later times, after tidal torques had begun to generate significant angular momentum, gas condensation in forming galaxies would have been increasingly inhibited by rotation, and the gas would have settled into increasingly extended disks. Therefore compact systems with large central gas concentrations like NGC 1705 may have been formed in abundance only at early times, while at later times mostly more diffuse rotationally supported systems would have formed. On larger scales the same trend, namely the general increase of angular momentum with time, would presumably have contributed to the early formation of centrally condensed elliptical galaxies and spiral bulges and the later building up of extended spiral disks.

A possibility which is consistent with the above suggestions is that some globular clusters may have originated as the nuclei of dwarf galaxies similar to the present nucleated dwarfs (Zinnecker et al. 1988; Freeman 1990, 1993; Bassino, Muzzio, & Rabolli 1994). NGC 1705, with its central 'super star cluster', may in fact be an example of the (rare) recent formation of a central massive cluster in a nucleated dwarf galaxy (Meurer et al. 1992; Freeman 1993).

In the context of current cosmological models, the progenitor systems of the globular clusters were presumably formed at the highest density peaks in the early universe, as suggested by West (1993). Since these highest peaks were strongly clustered in the densest regions of the universe, the formation of globular clusters would then have been 'biased' to occur preferentially in these regions, and this could explain the exceptionally high frequency of globular clusters in some giant galaxies such as M87 which are located at the centers of large clusters of galaxies (Harris 1991, 1993; West 1993). This property of globular cluster systems is not accounted for by most theories of their formation, but it seems to point to a close connection between globular clusters and cosmology, and suggests that the globular clusters are fossil remnants of the earliest condensed structures to form in the densest parts of the universe.

We have so far considered only the globular clusters in the halos of galaxies, but the most metal-rich globular clusters in our Galaxy are actually not in the halo but in a more compact and flattened configuration similar to, and perhaps identical with, the Galactic thick disk component (Zinn 1985; Armandroff 1993). Thus, it is apparently possible for globular clusters to form in large disks as well as in small halo subsystems. Even the disk globular clusters in our Galaxy were formed only at early times, however, and during the past 10 Gyr the Galactic disk has produced only smaller open clusters. What evolution in the properties of a disk might account for the formation of the most massive disk clusters only at the earliest times?

As was noted by Larson (1988, 1992b), there is a maximum length scale over which self-gravity can be important in a disk, and it is essentially the 'critical wavelength' $\lambda_{\rm crit}$ derived by Toomre (1964); in spiral galaxies, this length scale determines the typical spacing of the spiral arms. In the simple case of a disk with constant surface density Σ and angular velocity Ω, the maximum wavelength for which gravitational instability is possible is given by $\lambda_{\rm crit} = \pi^2 G\Sigma/\Omega^2$, and the associated maximum mass scale is $M_{\rm crit} = \lambda_{\rm crit}^2 \Sigma = \pi^4 G^2 \Sigma^3/\Omega^4$. In typical present-day spiral galaxies, $\lambda_{\rm crit}$ is of the order of 1 kpc and $M_{\rm crit}$ is of the order of $10^7\,M_\odot$, and these values are comparable to the sizes and masses of the spiral-arm segments which are the largest star-forming units in such galaxies. However, in the first disks to form, including the early disk of our Galaxy, the gas surface density Σ might have been higher and the angular velocity Ω might have been smaller than in typical present-day galaxies, and these differences could have resulted in a much larger maximum self-gravitating mass $M_{\rm crit}$ because of the strong dependence of $M_{\rm crit}$ on both Σ and Ω. Gas surface densities might have been higher initially because less of the gas had been converted into stars, and angular velocities might have been smaller because the first condensed systems to form had relatively little angular momentum, as noted above. Even modest differences in either parameter could plausibly have led to predicted values of $M_{\rm crit}$ larger than $10^8\,M_\odot$, the apparent minimum mass required for a star-forming complex to form a globular cluster. To the extent that the halo subsystems discussed above may themselves have been rotationally flattened, similar considerations would apply to them as well, and could explain why the most massive halo clusters are all relatively old while the youngest ones are all relatively small, as noted in Section 2.

It may be noted that there also is evidence for many galaxies other than our own suggesting a decrease with time in the typical masses of the clusters formed. The globular clusters are generally bluer and more metal-poor than the field stars in giant elliptical galaxies (Harris 1991, 1993; Brodie 1993) and in Local Group dwarfs (Da Costa & Armandroff 1995), and this fact, together with the fact that the globular clusters have a more extended spatial distribution than the field stars in elliptical galaxies (Harris 1991, 1993), suggests that the globular clusters were formed before the bulk of the field stars in these galaxies (Larson 1988; Harris 1993). Since nearly all stars are apparently formed in clusters of some kind (Section 4), the field stars must mostly have been formed in smaller clusters that have not survived because of their shorter lifetimes; therefore star formation must generally have produced smaller clusters at later times.

In summary, much evidence indicates that the most massive clusters in galaxies were formed at the earliest times, and this could have been because the first star-forming systems, whether small protogalactic fragments or larger disks, had smaller angular momenta or higher gas surface densities than typical present-day galaxies; both differences would have favored the formation of more massive gas concentrations and hence more massive clusters at earlier times. At the present time, conditions sufficiently extreme to form globular-like clusters are apparently found only in the relatively rare starburst galaxies, where violent disturbances or large dark-matter concentrations may have caused the gas to collect into massive complexes.

6. The Sagittarius Dwarf Galaxy: Halo Formation in Progress

A dramatic illustration of halo formation in progress is provided by the recently discovered Sagittarius dwarf galaxy, which is just now being tidally disrupted and merged with the halo of our Galaxy (Ibata, Gilmore, & Irwin 1994; Mateo et al. 1995; Sarajedini & Layden 1995; Da Costa & Armandroff 1995; Irwin et al. 1996; Gilmore 1996). If classified as a dwarf spheroidal galaxy, the Sagittarius dwarf becomes the most luminous of the nine such dwarfs now known to be associated with our Galaxy, and the third most luminous satellite after the Large and Small Magellanic Clouds. It has a moderately old and metal-poor field population similar to that of the other dwarf spheroidal galaxies, and it contains the four previously known globular clusters M54, Arp 2, Ter 7, and Ter 8. It is also by far the closest satellite of our Galaxy, being well within the Galactic halo at a distance of 16 kpc from the center, and its great elongation and diffuseness and its orbital characteristics (Velázquez & White 1995; Johnston, Spergel, & Hernquist 1995) leave little doubt that it is currently being tidally dispersed after a recent passage closer to the Galactic center. Its remnants will almost certainly form a moving stream in the Galactic halo, perhaps similar to the streams whose existence has been suggested by Majewski (1996). In particular, its four globular clusters will be dispersed into the general halo population of clusters, contributing to the outer Galactic halo four globular clusters whose origin was unquestionably in a dwarf satellite galaxy.

The globular cluster population of the Sagittarius dwarf is also of interest in that it traces a long history of star formation and chemical enrichment in this small galaxy, extending from Ter 8 with an age of about 19 Gyr and a metallicity of -2.0 to Ter 7 with an age of about 9 Gyr and a metallicity of -0.4 (ages are from Chaboyer et al. 1996 and metallicities are from Da Costa & Armandroff 1995). Arp 2 is intermediate in age and metallicity, having an age of about 13 Gyr and a metallicity of -1.7, while M54 has an intermediate metallicity of about -1.6 but does not yet have a well-determined age. These properties provide a clear illustration that the age spread among the outer halo clusters does not necessarily reflect the merger history of the halo, but may originate mainly from a long period of cluster formation in the accreted satellite systems.

The most interesting feature of the Sagittarius dwarf from the perspective of understanding the origin of the globular clusters is the presence at its center of the classical outer halo globular cluster M54, which is the second most luminous globular cluster in our Galaxy after ω Cen (Sarajedini & Layden 1995). The location of this cluster at the position of the peak surface density of the Sagittarius dwarf, and the fact that its distance and radial velocity lie at the centers of the distributions of these quantities for the field stars and other clusters in this galaxy, leave no question that M54 is the central dominant object or 'nucleus' of the Sagittarius dwarf galaxy. It has been debated whether M54 should be called the 'nucleus' of this galaxy (Sarajedini & Layden 1995; Da Costa & Armandroff 1995; Bassino & Muzzio 1995), but the latter authors suggest that this galaxy is indeed a nucleated dwarf, and that this can account for its longevity in close proximity to our own Galaxy. In any case, the Sagittarius dwarf provides a clear example of the formation of a very massive cluster near the center of a dwarf galaxy, and it may represent a later stage of evolution of systems like NGC 1705 with its central 'super star cluster' (Section 4). The fact that the Sagittarius dwarf is presently being tidally dispersed means that M54 is just now being deposited into the halo of our Galaxy, at a time when we can still catch a glimpse of its origin as the central object of a dwarf galaxy. This example demonstrates convincingly that some of the globular clusters in the halo of our Galaxy, including even some of the most massive ones, have originated in satellite systems resembling the protogalactic fragments postulated by Searle & Zinn (1978) and predicted by current cosmological models.

If our Galaxy is just now accreting a satellite galaxy, this suggests that similar accretion events may have continued throughout Galactic history, as would be predicted in a high-density universe. Such continuing accretion of small satellite systems is not necessarily incompatible with the survival of a thin disk in our Galaxy, because most of the accreted systems may be tidally disrupted while still in the halo and so may not significantly disturb the disk (Navarro, Frenk, & White 1994). The halo of our Galaxy could then contain, or consist of, the debris from a long series of accretion events that contributed to the building up of our Galaxy. A major challenge for students of Galactic structure will be to try to reconstruct from the fossil remnants now scattered throughout the halo a record of the building of our Galaxy from the now mostly extinct progenitor systems whose 'bones' still survive as the globular clusters.

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