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The Formation of Globular Cluster Systems

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Abstract. I briefly review models for the formation of globular cluster (GC) systems, and summarize the observational properties (*i.e.*, formation efficiencies, metallicity distributions, kinematics and ages) of the GC systems of M87 and M49: two thoroughly-studied elliptical galaxies. Many of the properties of the metal-poor GCs in these and other galaxies appear to be consistent with their formation in low-mass proto-galactic fragments, as proposed by several different formation models. A number of outstanding questions concerning the formation of the metal-rich GCs in these galaxies are highlighted.

1. Introduction

The past decade has witnessed a remarkable advance in our understanding of globular cluster (GC) systems. Optical and ultraviolet imaging from *HST* has been used to study GC systems belonging to nearly one hundred (mostly early type) galaxies. Spectra from 4-10m class telescopes have yielded radial velocities for more than a thousand extragalactic GCs, along with metallicities for subset of the brighter objects. Infrared photometry for extragalactic GCs is appearing in the literature at an ever-increasing rate, promising to refine our understanding of how these systems formed and evolved.

Indeed, theorists are now hard pressed to produce a single model for the formation of GC systems that explains — or, at least, is consistent with — the enormous amount of observational material that has been accumulated. This is a daunting task, since any viable formation model must reproduce and explain the apparently constant number of GCs per unit baryonic mass, the striking complexity of GC metallicity distribution functions (MDFs), the observed spatial distributions of GCs about their host galaxy, and the emerging constraints on the ages and kinematics of the metal-poor (MP) and metal-rich (MR) GC subpopulations. What is ultimately required is a model that explains not just these observational properties, but also their variations (if any) with host galaxy environment and morphology. Although several important issues remain unresolved, I will argue below that there may be an emerging consensus on the origin of the MP GC subpopulations associated with bright galaxies. The origin of the MR subpopulation remains very much open to debate.

2. Formation Scenarios

It is convenient to divide models for the formation of GC systems into three broad categories: pre-, proto- and post-galactic. While these divisions are useful for heuristic purposes, they should not be taken too literally since the classification is, in some cases, rather subjective. It is also worth noting that some models that have historically been considered quite distinct (*e.g.*, Ashman & Zepf 1992 and Côté *et al.* 1998) actually rely on similar mechanisms — mergers and accretions — to explain the formation of GC systems. These models differ mainly the assumed nature of the merger/accretion process: most notably in the assumed mass spectrum of the progenitors, the epoch of galaxy assembly, and the amount of dissipation and star/GC formation (if any) induced by the merger/accretion process.

Pre-galactic: In this picture, the formation of GCs predates that of their host galaxy. First suggested by Dicke & Peebles (1968), who noted that the Jeans mass at recombination was similar to the mean mass of Galactic GCs, this model was later revised by Peebles (1984) to explain GC formation in a cold dark matter (CDM) dominated universe. We now recognize the GC mass distribution to have a roughly double power-law form with a break at $M \sim 10^5\ M_{\odot}$, weakening the original Jeans mass argument.

Recently, Cen (2001) has proposed a variant of this model in which the MP GCs surrounding galaxies form during reionization, when the external radiation field produces inward shocks in low-mass, low-spin dark matter halos. Such shocks, he argues, will compress the baryons and lead to the formation of GCs. While this model gives roughly the correct mass spectrum for GCs more massive than about $10^5\ M_{\odot}$, the mechanism itself is quite unlike that observed in star- and cluster-forming molecular clouds in the local universe (and leaves the formation of the MR GCs unexplained). Moreover, it seems inevitable that this model should predict many intergalactic GCs in the local universe. Although the properties of some GCs associated with a few galaxies like M87 are consistent with an intergalactic origin (see Côté *et al.* 2001), there is still no case in which even a single GC can be said with certainty to be truly intergalactic in nature.

Proto-galactic: It was suggested by Harris & Pudritz (1994) that GCs form within the dense cores of supergiant molecular clouds (SGMCs): *i.e.*, an hypothesized population of pressure-confined, self-gravitating, isothermal, magnetized clouds. These SGMCs, they argued, were supported against gravitational collapse by magnetic field pressure and Alfvénic turbulence. Though most SGMCs would presumably have been disrupted during the assembly of the host galaxy, any surviving SGMCs would, if left in isolation, have masses of $M \sim\ 10^9\ M_{\odot}$ and diameters of $D \sim\ 1$ kpc. In short, they would resemble dwarf galaxies.

Subsequent cosmological N-body/TREESPH simulations by Weil & Pudritz (2001) confirmed that gravitationally-bound objects having masses and sizes similar to these SGMCs do indeed form, and that they have a roughly power-law mass spectrum, $N(M) \propto M^{\alpha} dM$, with $\alpha \sim -1.7$. Since star and GC formation was not included in their simulations, no conclusion could be drawn regarding GC MDFs.

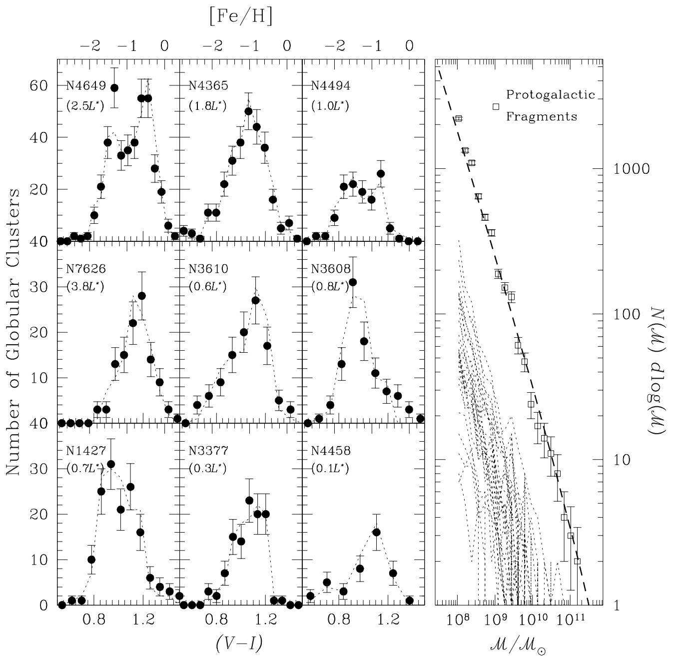

Figure 1. (Left Panels) Representative color/metallicity distributions for GCs belonging to nine of the 28 galaxies in the study of Kundu & Whitmore (2001). The galaxy name and its luminosity in units of L^* are given in each panel. In each case, the best-fit distribution obtained from Monte-Carlo simulations of hierarchical galaxy formation is shown by the dashed curve (Côté *et al.* 2002). (Right Panel) Individual and combined mass spectra of proto-galactic fragments for the same 28 galaxies (dotted curves and open squares, respectively). The dashed line shows a Press-Schechter (1974) mass function with $M^* = 5 \times 10^{11} M_{\odot}$ and $n = -2$, where n is the index of the cosmological power spectrum.

An empirical method of studying GC MDFs has been has been explored in a series of papers by my collaborators and I (Côté *et al.* 1998, 2000, 2002) where a Monte-Carlo algorithm was developed to simulate the GC MDFs of galaxies that are assembled from "proto-galactic fragments". In this picture, both the total number of GCs and their metallicities are determined solely by the mass of the proto-galactic fragment in which they formed; no GCs are formed during the merger and accretion process. The left panels of Figure 1 show simulated and observed MDFs for nine of the 28 galaxies examined in Côté *et al.* (2002). The right panel shows proto-galactic mass spectra for the 28 galaxies, along with the ensemble mass spectrum. These simulations suggest that the mass spectrum of proto-galactic fragments had an approximate power-law form with index $\alpha \sim -1.8$, in close agreement with the N-body results.

It is remarkable that two completely independent lines of evidence (*i.e.*, N-body simulations of the gravitational collapse of primordial density fluctuations and Monte-Carlo simulations of the GC MDFs) point to a steep proto-galactic mass spectrum. Although this agreement lends credibility to the results, it is important to recall that the inferred mass spectrum is *much* steeper than measured luminosity function of galaxies in the local universe. Thus, the formation of GC systems seems inevitably linked to the so-called "missing satellite" problem (Klypin *et al.* 1999; Moore *et al.* 1999).

In a recent paper that further demonstrates the utility of GC systems in constraining cosmological models of galaxy formation, Beasley *et al.* (2002) used the GALFORM semi-analytic code to simulate the GC systems of 450 elliptical galaxies. The relative number of MP and MR GCs in their simulations — which include shock heating of the gas, radiative cooling, feedback, mergers and stellar evolution — were then compared to the observed numbers in M49, where the census of GCs is very nearly complete. This comparison revealed that two *ad hoc* assumptions were necessary to reproduce the MP and MR GCs in the correct numbers. First, the formation efficiency of MR GCs must exceed that of MP GCs by a factor of $\approx$ 3-4 (see below for an examination of the plausibility of this assumption). Second, the formation of MP GCs, which occur in low-mass halos that Beasley *et al.* term "proto-galactic disks", must be truncated abruptly at $z_{\rm trunc} \simeq 5$. Without these assumptions, the predicted population of MP GCs would dominate the MR population by up to two orders of magnitude at $z = 0$. Unlike previous simulations, Beasley *et al.* were able to estimate *ages* for the GCs. The MP GCs have, by virtue of the assumed value of $z_{\rm trunc}$, a mean age of $T \simeq 12$ Gyr. The MR GCs are then found to be 1–7 Gyr younger, with a mean age difference of 3 Gyr, although this too hinges on the assumed $z_{\rm trunc}$.

Post-Galactic: Building upon a suggestion by Schweizer (1987), Ashman & Zepf (1992) examined the possibility that a factor-of-two difference in specific frequency, S_N, between normal elliptical and spiral galaxies (*e.g.*, Harris 1991) might be explained if: (1) normal elliptical galaxies formed as a result of major mergers of disk galaxies, and (2) the merger process led to the formation of new, presumably MR, GCs. There seems to be little doubt that a process of this sort has played in role in the formation of some elliptical galaxies, in light of the detection of young clusters forming in interacting galaxies (*e.g.*, Whitmore *et al.* 2001). But is it plausible that major mergers of disk-galaxy pairs is the *generic* mechanism for the formation of normal elliptical galaxies, more than half of which show bimodal GC MDFs (*e.g.*, Larsen *et al.* 2001)?

The most comprehensive study of GC formation in disk mergers is that of Bekki *et al.* (2002), who used an N-body/TREESPH code to investigate mergers of pairs of gas-rich disk galaxies. These disks were *posited* to contain a pre-existing population of exclusively MP GCs. Using a simple pressure criterion for the onset of GC formation, Bekki *et al.* showed that the end-products of such mergers do indeed resemble elliptical galaxies, with distinct MP and MR GC subpopulations. The newly-formed MR GCs show a greater degree of concentration toward the center of the merger remnant, as is observed. Bekki *et al.* also examined the kinematic properties of the MP and MR GC subpopulations, finding the MP component to show a large velocity dispersion and a net rotation; by contrast, the MR component was found to show a lower dispersion and modest rotation. By examining the GC MDFs of the merged galaxy, Bekki *et al.* also noted that the mean metallicity of the MR GCs far exceeded those measured for MR GCs in real ellipticals. As no plausible change in the assumed range of gas metallicities, abundance gradients in the progenitor disks, or GC

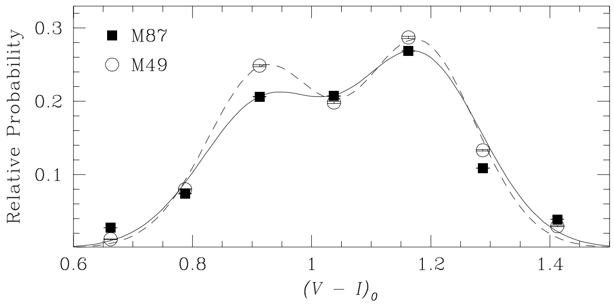

Figure 2. Color distributions for GCs belonging to M87 and M49, based on *HST* photometry from Kundu *et al.* (1999) and Kundu & Whitmore (2001). The solid and dashed curves for the best-fit double Gaussians used to estimate the GC formation efficiencies given in Table 1. The relative numbers of MP and MR GCs in the two galaxies is remarkably similar, despite the factor of 2-3 difference in specific frequency.

formation criteria was able to alter this basic result, they concluded that "if most elliptical galaxies are formed by major mergers, then it must have occurred at high redshift".

3. The Globular Cluster Systems of M87 and M49 Compared

Let us now consider how the various models fare in explaining the GC systems of real ellipticals. I will focus on a comparison of two thoroughly-studied ellipticals: M49 and M87, the first- and second-ranked members of the Virgo cluster, respectively. Although they differ in V-band luminosity by only $\sim 20\%$, the GC specific frequency of M87 exceeds that of M49 by a factor of 2-3 (Harris 1991). Together, these galaxies form a "second parameter" pair in terms of their GC systems, and any viable formation scenario must account for the observed differences and similarities.

The primary motivation of the Ashman & Zepf (1992) merger model was an explanation of the higher specific frequencies of early-type galaxies relative to disk galaxies. In this picture, mergers serve to increase specific frequency through the formation of MR GCs. Thus, galaxies with high specific frequencies — of which M87 is the prototype — are expected to have predominantly MR GC systems according to this model. In the specific case of M87, this "excess" population relative to M49 should amount to ≈ 7000 *additional* MR GCs.

As Figure 3 shows, this expectation is not borne out by the observations. The measured GC color distributions for the two galaxies (based on deep HST imaging in identical filters from Kundu *et al.* 1999 and Kundu & Whitmore 2001) are remarkably similar. Parameterizing each distribution with a double-Gaussian yields the percentages of MP and MR GCs given in Table 1. This table also give the total number of GCs belonging to each galaxy, $N_{\rm tot}$, from McLaughlin (1999), who showed that the observed difference in specific frequency between these two galaxies is likely due to the greater mass in X-ray emitting gas in the vicinity of M87.

Table 1. GC Formation Efficiencies for M87 and M49

	M87	M49
N_{tot}	13,600±600	6,850±550
ϵ_{tot}	0.28±0.04%	0.23±0.05%
f_{MP}	57±5%	54±5%
f_{MR}	43±5%	46±5%
ϵ_{MP}	0.16±0.03%	0.12±0.03%
ϵ_{MR}	0.12±0.02%	0.11±0.03%

Defining the GC formation efficiency, ϵ_{tot}, as the total mass in GCs normalized to the total baryonic mass (*i.e.*, stars and gas), McLaughlin found the GC formation efficiencies given in Table 1. The overall efficiency with which GCs formed in M87 and M49 are not only consistent with each other, they are indistinguishable from the "universal" GC formation efficiency of $\langle\epsilon_{tot}\rangle = 0.26\pm0.05\%$ found by McLaughlin (1999) from an analysis of nearly one hundred early-type galaxies (see also Blakeslee *et al.* 1997). In any event, it is clear from Table 1 and Figure 1 that the similar *relative* number of MP and MR GCs in the two galaxies is certainly at odds with the predictions of the merger model.

Combining the values of f_{MP} and f_{MR} from Table 1 with McLaughlin's best estimates for ϵ_{tot} in the two galaxies, I find the values of ϵ_{MP} and ϵ_{MR} given in Table 1. To within the uncertainties, the MP and MR GC systems have identical formation efficiencies. The observed values of ϵ_{MP} are roughly consistent with the formation efficiency of MP GCs, $\epsilon_{MP} = 0.2\%$, used by Beasley *et al.* (2002) in their semi-analytic simulations. However, their assumed value of $\epsilon_{MR} = 0.7\%$ exceeds the measured value by a factor of six. Strictly speaking, the GC formation efficiencies in Table 1 are measured relative to the *baryonic* mass, whereas those of Beasley *et al.* are measured with respect to the *total* mass (*i.e.*, including dark matter). However, inside $\sim$ 50 kpc, the R-band mass-to-light ratios of M49 and M87 are virtually identical, with $\Upsilon_R \sim 35$ (Côté *et al.* 2001; 2003), so the comparison should be valid in this case.

Table 2. Kinematics of GC Subpopulations in M87 and M49

	M87			M49		
	$\langle\sigma_p\rangle$ (km s^{-1})	$\langle\Omega R\rangle$ (km s^{-1})	$\langle\Omega R/\sigma_p\rangle$	$\langle\sigma_p\rangle$ (km s^{-1})	$\langle\Omega R\rangle$ (km s^{-1})	$\langle\Omega R/\sigma_p\rangle$
All	383^{+31}_{-7}	171^{+39}_{-30}	0.45±0.09	316^{+27}_{-8}	48^{+52}_{-26}	$0.15^{+0.15}_{-0.08}$
MP	397^{+36}_{-14}	186^{+58}_{-41}	$0.47^{+0.13}_{-0.11}$	342^{+33}_{-18}	93^{+69}_{-37}	$0.27^{+0.19}_{-0.11}$
MR	365^{+38}_{-18}	155^{+53}_{-37}	$0.43^{+0.14}_{-0.12}$	265^{+34}_{-13}	-26^{+64}_{-79}	$0.10^{+0.27}_{-0.25}$

Now let us examine the kinematical properties of the two GC systems. A dynamical analysis of the M87 GC system based on Washington photometry and radial velocities for 278 confirmed GCs was presented recently in Côté *et al.*

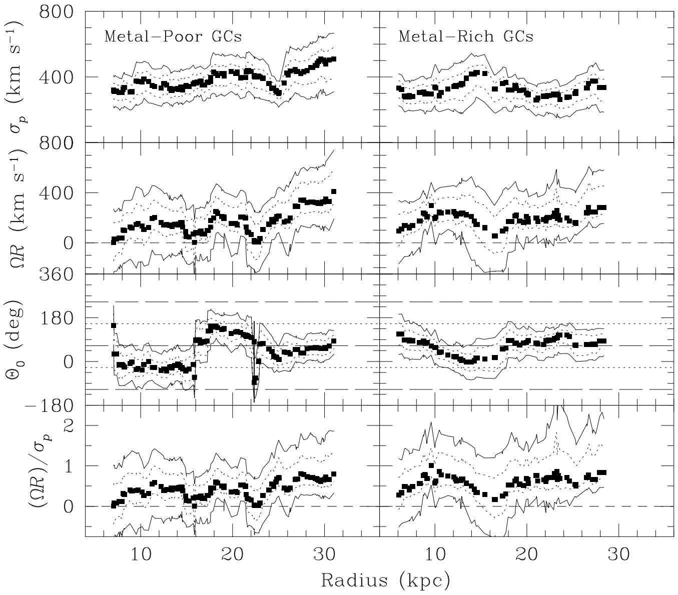

Figure 3. Kinematic properties of GCs in M87. The panels show smoothed profiles for the velocity dispersion, rotation amplitude, position angle of the rotation axis, and the ratio of rotation amplitude to line-of-sight velocity dispersion. The dashed and dotted lines in the third panels show the orientation of the galaxy's minor and major axes, respectively. Results for the MP GCs are shown on the left; MR GCs are on the right. Only those points that are separated by more than $90'' \simeq 6.5$ kpc are independent. The dotted and solid curves show the 68% and 95% confidence intervals on measured parameters.

(2001) and a similar analysis for the M49 GC system, based on velocities for 263 GCs, is now underway (Côté *et al.* 2003). Figure 2 shows the radial variation in kinematic parameters (*i.e.*, velocity dispersion, σ_p, projected rotation amplitude, ΩR, position angle of the rotation axis, Θ_0, and the ratio of rotation amplitude to velocity dispersion, $\Omega R/\sigma_p$) for the MP and MR GCs in M87. Global results for the two galaxies are presented in Table 2.

A detailed discussion of the results is beyond the scope of this review, but the main findings can be summarized as follows. In M87, both the MP and MR GC systems show significant rotation, with $\langle \Omega R/\sigma \rangle \approx 0.45$. The MR GCs rotate about the galaxy's minor axis everywhere, as do the MP GCs beyond $R \sim 15$ kpc. Inside this radius, however, the MP GCs appear to rotate about the *major* axis. In the case of M49, the MP GCs show modest minor axis rotation everywhere, with $\langle \Omega R/\sigma_p \rangle \simeq 0.27$, while the MR GCs show little or no rotation. (The formal best-fit actually suggests that the MR GCs are counter-rotating).

Clearly, the GC subsystems in M87 and M49 show some rather dramatic kinematic differences. This apparent complexity becomes is all the more puzzling when one considers that the two spiral galaxies have the best studied GC systems, the Milky Way and M31, have $\langle \Omega R/\sigma \rangle \simeq 0.32$ and $\langle \Omega R/\sigma \rangle \simeq 0.85$ for the MP components, respectively. For their MR GC subpopulations, rotation is even more important, with $\langle \Omega R/\sigma \rangle \simeq 1.05$ and $\langle \Omega R/\sigma \rangle \simeq 1.10$ respectively (Côté 1999; Perrett *et al.* 2002).

What implications do these results have for GC formation models? First, the rotation observed for MP GCs in these galaxies suggests that, if these GCs did indeed originate in numerous, low-mass proto-galactic fragments as suggested by several of the "proto-galactic" models discussed above, then these low-mass fragments must first have coalesced into larger entities before being incorporated into the final galaxy (assuming that the observed rotation reflects the orbital angular momentum of the progenitor galaxies). Secondly, the rapid rotation among the MR GCs in M87 (and in the two spirals) indicates that their formation in mergers may be unlikely, given that angular momentum transport should produce a slowly rotating population. On the other hand, the MR GCs in M49 are consistent with no net rotation, suggesting that angular momentum transport during a major merger may have been effective in this case.

Finally, I consider the critical issue of ages for the MP and MR GCs subpopulations in these galaxies, focusing on two complementary techniques that have been brought to bear upon this issue: integrated-light spectroscopy, and the magnitude difference between the turnovers of the GC luminosity functions (LFs) for the GC subpopulations. The former technique yields absolute ages for the GC subpopulations, while the latter approach gives only their relative ages.

The various age measurements are summarized in Table 3, which reports $\Delta T \equiv T_{\rm MP} - T_{\rm MR}$ for each GC subpopulation and, when available, the corresponding absolute ages. In the case of M87, the spectroscopy of Cohen *et al.* (1998) suggests an old age for both components, with no evidence for a trend between age and metallicity. On the other hand, Kundu *et al.* (1999) found a rather large age difference from the V and I luminosity functions, with the MR GCs being several Gyr younger. A more recent application of this technique, however, which relies on Strömgren photometry from from *HST* and makes use of the greater age sensitivity of the u-band, points to a very small age difference, in agreement with the spectroscopic results (Jordán *et al.* 2002). For M49, both techniques indicate that the GC subpopulations are coeval to within the measurement errors.

Table 3. Age Determinations for GC Subpopulations in M87 & M49

Galaxy	$T_{\rm MP}$	$T_{\rm MR}$	$\Delta T \equiv T_{\rm MP} - T_{\rm MR}$	Source	Ref.
M87	13.7±1.8	12.7±2.2	+1.0±3.3	Spectra	1
	⋯	⋯	≈3–6	LF (VI)	2
	⋯	⋯	+0.2±1.5(sys.)±2.0(ran.)	LF ($uvby$)	3
M49	⋯	⋯	−0.6±3.2	LF (VI)	4
	14.5±4	13.8±6	+0.7±7.2	Spectra	5

REFERENCES: (1) Cohen *et al.* (1998); (2) Kundu *et al.* (1999); (3) Jordán *et al.* (2002); (4) Puzia *et al.* (1999); (5) Beasley *et al.* (2000).

The agreement between the photometric and spectroscopic results is generally encouraging. For these two galaxies at least, the MP and MR GCs seem to be truly old objects. Although the error bars remain large, it seems that, if GC formation in mergers of any sort — minor or major — has played the dominant role in producing the MR GCs in these galaxies, then the merger/assembly process must have occurred at high redshift (*i.e.*, $z \gtrsim 4$ in the currently fashionable ΛCDM models). In my opinion, these results suggest that the disparate metallicities of the GC subpopulations in these galaxies likely reflect *environmental* differences in the local sites of GC formation.

4. Conclusions

In both M87 and M49, the efficiency of GC formation is found to have the familiar "universal" value of $\epsilon_{\rm tot} \simeq 0.25\%$ per unit baryon mass (McLaughlin 1999). In both galaxies, the formation efficiencies of the separate MP and MR components is roughly half that of the GC system as a whole. These findings provide a challenge to models in which MR GCs form exclusively in major mergers, and to models that require different formation efficiencies for the MP and MR GCs.

Kinematic studies of the GC subpopulations in M87 and M49 reveal some interesting differences. In M87, both GC subpopulations show rapid rotation; in M49, the MP GCs show modest rotation, while the MR GCs form a non-rotating population. The existence of rapidly rotating GC subpopulations in these galaxies, and in the Milky Way and M31, suggests that mergers have probably played a role in the formation of the host galaxies, as the amount of angular momentum involved seems to exceed that generated by tidal torques alone (see Côté *et al.* 2001). With the exception of M49, the rapidly rotating MR GCs in these galaxies indicate that the formation of the MR GCs probably predated the mergers. Furthermore, the ages of the GC subpopulations in M87 and M49 suggest that if the mergers were predominantly dissipational in nature, then the mergers must have occurred at high redshift, as noted by Bekki *et al.* (2002) from an analysis of simulated and observed GC MDFs.

Many properties of the MP GCs in M87 and M49 (and in other galaxies) are consistent with the predictions of models in which these GCs form in low-mass, proto-galactic fragments that are later accreted into the main body of the galaxy. These proto-galactic fragments appear to be the analogs of the low-mass subhalos that form in cosmological simulations of structure formation. Indeed, the literature abounds with terminology for these objects: *e.g.*, proto-galactic fragments, supergiant molecular clouds, proto-galactic disks, Searle-Zinn fragments, failed dwarfs, *etc.* In terms of their physical properties, however, these are the same objects.

While there may be an emerging consensus on the origin of the MP GCs, debate continues on the nature and origin of their MR counterparts. These clusters can be interpreted simply as those that formed in the most massive proto-galactic fragments, or as the endproducts of a star formation burst triggered by gas-rich mergers. The former interpretation has the æsthetic advantage of requiring a single mechanism to explain both GC populations, while the second scenario has strong support from observations of young GCs forming in local mergers. It is likely that both processes have played a part in shaping the GC systems that we observe today, and our task for the decade ahead is to determine which, if either, of these processes has played a dominant role.

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