Constraints on Cluster Formation from Old Globular Cluster Systems

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Abstract. The properties of old globular cluster systems (GCSs) in galaxy halos offer unique insight into the physical processes that conspire to form any generic star cluster, at any epoch. Presented here is a summary of the information obtained from (1) the specific frequencies (total populations) and spatial structures (density vs. galactocentric radius) of GCSs in early-type galaxies, as they relate to the efficiency (or probability) of bound cluster formation, and (2) the fundamental role of a scaling between cluster mass and energy among Galactic globulars in setting their other structural correlations, and the possible implications for star formation efficiency as a function of mass in gaseous protoclusters.

1. Introduction

Until quite recently, it was commonly assumed that the old globular clusters in galaxy halos were the remnants of a unique sort of star formation that occurred only in a cosmological context. The discovery of young, massive, “super” star clusters in local galaxy mergers and starbursts has clearly done much to change this perception; but at least as important is the parallel recognition that star formation in the Milky Way itself proceeds—under much less extreme conditions—largely in a clustered mode. Observations of entire starbursts (Meurer et al. 1995) and individual Galactic molecular clouds (e.g., Lada 1992), as well as a more general comparison of the mass function of molecular cloud clumps and the stellar IMF (Patel & Pudritz 1994), all argue convincingly that (by mass) most new stars are born in groups rather than in isolation. The production of a true stellar cluster—one that remains bound even after dispersing the gas from which it formed—is undoubtedly a rare event, but it is an exceedingly regular one.

Seen in this light, the globular cluster systems (GCSs) found in most galaxies can be used to good effect as probes not only of galaxy formation but also of an important element of the generic star-formation process at any epoch. This is arguably so even in cases where newly formed clusters may not be “massive” according to the criteria of this workshop (the main issue being simply the formation of a self-gravitating stellar system), and even though GCSs have
been subjected to $10^{10}$ yr of dynamical evolution in the tidal fields of their parent galaxies (see O. Gerhard’s contribution to these proceedings, and note that theoretical calculations geared specifically to conditions both in the Milky Way [Gnedin & Ostriker 1997] and in the giant elliptical M87 [Murari & Weinberg 1997] suggest that GCS properties are most affected by evolution inside roughly a stellar effective radius in each case).

2. The Efficiency of Cluster Formation

At some point during the collapse and fragmentation of a cluster-sized cloud of gas, the massive stars which it has formed will expel any remaining gas by the combined action of their stellar winds, photoionization, and supernova explosions. If the star formation efficiency of the cloud, $\eta \equiv M_{\text{stars}}/(M_{\text{stars}} + M_{\text{gas}})$, is below a critical threshold just when the gas is lost, then the blow-out removes sufficient energy that the stellar group left behind is unbound and disperses into the field. The precise value of this threshold depends on details of the internal density and velocity structure of the initial gas cloud, and on the timescale over which the massive stars dispel the gas; but various estimates place it in the range $\eta_{\text{crit}} \sim 0.2$–$0.5$ (e.g., Hills 1980; Verschueren 1990; Goodwin 1997, and these proceedings). There is no theory which can predict whether any given piece of gas can ultimately achieve $\eta > \eta_{\text{crit}}$, but it is straightforward to evaluate empirically the frequency—or efficiency—with which this occurs.

Traditionally, this has been discussed for GCSs in terms of specific frequency, defined by Harris & van den Bergh (1981) as the normalized ratio of a galaxy’s total GCS population to its V-band luminosity: $S_N \equiv N_{\text{tot}} \times 10^{0.4(M_V + 15)}$. As is well known (see, e.g., Elmegreen 2000 for a recent review), there are substantial and systematic variations in this ratio from one galaxy to another: Global specific frequencies decrease with increasing galaxy luminosity for early-type dwarfs, then increase gradually with $L_{V,\text{gal}}$ in normal giant ellipticals, and finally increase rapidly with galaxy luminosity among the central ellipticals (BCGs) in groups and clusters of galaxies. In addition, the more extended spatial distribution of GCSs relative to halo stars in some (but not all) bright ellipticals leads to local specific frequencies (ratios of GCS and field-star densities) that increase with radius inside the galaxies (see McLaughlin 1999).

However, McLaughlin (1999) shows (following related work by Blakeslee et al. 1997 and Harris et al. 1998) that these trends in $S_N$ do not reflect any such behavior in the ability to form globulars in protogalaxies. To see this, it is best to work in terms of an efficiency per unit mass, $\epsilon_{\text{cl}} \equiv M_{\text{gcs}}^{\text{init}} / M_{\text{gas}}^{\text{init}}$, where $M_{\text{gas}}^{\text{init}}$ is the total gas supply that was available to form stars in a protogalaxy (whether in a monolithic collapse or a slower assembly of many distinct, subgalactic clumps is unimportant) and $M_{\text{gcs}}^{\text{init}}$ is the total mass of all globulars formed in that gas. As McLaughlin (1999) argues, the integrated mass of an entire GCS should not be much affected by dynamical evolution, and it is most appropriate to include any gas presently associated with galaxies, as well as their stellar masses, in estimating their initial gas contents. The observable ratio $M_{\text{gcs}}/(M_{\text{gas}} + M_{\text{stars}})$ should therefore improve on $S_N \propto M_{\text{gcs}}/M_{\text{stars}}$ as an estimator of $\epsilon_{\text{cl}}$.

Figure 1 shows the total GCS populations vs. galaxy luminosity in 97 early-type galaxies and the metal-poor spheroid of the Milky Way and compares the
expectations for a constant $\epsilon_{cl} = 0.26\%$, given both the variation of stellar mass-to-light ratio with $L_{V,\text{gal}}$ on the fundamental plane of ellipticals and the increase of $M_{\text{gas}}/M_{\text{stars}}$ with $L_{V,\text{gal}}$ for regular gE’s and BCGs inferred from the correlation between their X-ray and optical luminosities (bold solid curve; see McLaughlin 1999), and after correcting (according to the model of Dekel & Silk 1986) for the gas mass lost in supernova-driven winds from early bursts of star formation in faint dwarfs ($L_{V,\text{gal}} \leq 2 \times 10^9 L_\odot$; bold dashed line). All systematic variations in GCS specific frequencies reflect only different relations, in different magnitude ranges, between $M_{\text{gas}}^{\text{init}}$ and the present-day $L_{V,\text{gal}}$.

McLaughlin (1999) also shows that the ratio of local densities, $\rho_{\text{GCS}}/(\rho_{\text{gas}} + \rho_{\text{stars}})$, is constant as a function of galactocentric position (beyond a stellar effective radius) in each of the large ellipticals M87, M49, and NGC 1399, and that this ratio is the same in all three systems: $\epsilon_{cl} = 0.0026 \pm 0.0005$. Moreover, it seems (although the data are much less clear in this case) that the same efficiency also applies to the ongoing formation of open clusters in the Galactic disk. It therefore appears that there is a universal efficiency for cluster formation, whose value should serve as a strong constraint on very general theories of star formation. (Note that one exception to the figure of 0.26% by mass may be the formation of massive clusters in mergers and starbursts, where it has been suggested that $\epsilon_{cl} \sim 1$–10% [e.g., Meurer et al. 1995; Zepf et al. 1999]. However, this conclusion is very uncertain and requires more careful investigation.)

While this result certainly has interesting implications for aspects of large-scale galaxy formation (McLaughlin 1999; Harris et al. 1998), the main point
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to be emphasized here is that the variations in early-type GCS specific frequencies are now understood to result from variations in the gas-to-star mass ratio in galaxies, rather than from any peculiarities in their GCS abundances per se (cf. the similar suggestion of Blakeslee et al. 1997). That is, the efficiency of unclustered star formation was not universal in protogalaxies: while globulars apparently always formed in just the numbers expected of them, the formation of a normal proportion of field stars was subsequently disabled in many cases. The clumps of gas which formed bound clusters therefore must have collapsed before those forming unbound groups and associations, i.e., they must have been denser than average. This and the insensitivity of $\epsilon_{cl}$ to local or global galaxy environment together suggest that quantitative theories of cluster formation should seek to identify a threshold in relative density, $\delta \rho / \rho$, that is always exceeded by $\approx 0.26\%$ of the mass fluctuations in any large star-forming complex.

3. Globular Cluster Binding Energies

Even as they clarify the probability that a $\sim 10^5$–$10^6 M_\odot$ clump of gas was able to form stars with cumulative efficiency $\eta$ high enough to produce a bound globular cluster, the integrated GCS mass ratios in galaxies say nothing of how this was achieved in any individual case. This more ambitious question is essentially one of energetics—When does the energy injected by the massive stars in an embedded young cluster overcome the binding energy of whatever gas remains, thus expelling it and terminating star formation?—and its answer requires both an understanding of local star formation laws ($d\rho_{stars}/dt$ as a function of $\rho_{gas}$) and a self-consistent treatment of feedback on small ($\sim 10$–$100$ pc) scales. One way to begin addressing this complex problem empirically is to compare the energies of globular clusters with the initial energies of their gaseous progenitors. McLaughlin (2000) has calculated the $V$-band mass-to-light ratios of 39 regular (non–core-collapsed) Milky Way globulars, and finds that they are all consistent with a single $\Upsilon_{V,0} = (1.45 \pm 0.10) M_\odot L_\odot^{-1}$. Applying this to all other Galactic globulars, and adopting single-mass, isotropic King (1966) models for their internal structure, then allows binding energies $E_b$ to be estimated for a complete sample of 109 regular (and 30 post–core-collapse) objects. This exercise reveals a very tight correlation between $E_b$, total cluster luminosity $L$ (or mass $M = \Upsilon_{V,0} L$), and Galactocentric position: $E_b = 7.2 \times 10^{39}$ erg $(L/L_\odot)^{2.05} (r_{gc}/8 \text{ kpc})^{-0.4}$, with uncertainties of roughly $\pm 0.1$ in each of the fitted exponents on $L$ and $r_{gc}$ (cf. Saito 1979, who claimed $E_b \propto M^{1.5}$ on the basis of a much smaller dataset).

These constraints on $\Upsilon_{V,0}$ and for $E_b(L, r_{gc})$ are, in fact, two edge-on views of a fundamental plane in the (four-dimensional) parameter space of King models, to which real globulars are confined in the Milky Way (cf. Djorgovski 1995; Bellazzini 1998). The full characteristics of this plane subsume all other observable correlations between any combination of other cluster parameters (see McLaughlin 2000), and they therefore provide a complete set of independent facts to be explained in any theory of globular cluster formation and evolution. In fact, the $E_b$–$L$ correlation is stronger among clusters at larger Galactocentric radii (where dynamical cluster evolution is weaker), suggesting that it was set largely by the cluster formation process. The same is true of a weaker correla-
tion between cluster concentration and luminosity (see Vesperini 1997), which is related to the distribution of globulars on the fundamental plane.

Any collection of critically stable, virialized gas spheres under a surface pressure $P_s$ have a common column density, $\Sigma \equiv M/(\pi R^2) \propto P_s^{0.5}$, and thus $E_{b,}\text{gas} \equiv GM^2/R \propto M^{1.5}P_s^{0.25}$. Harris & Pudritz (1994) have developed a physical framework in which protoglobular clusters in the Milky Way were massive analogues of the dense clumps in disk molecular clouds today; in particular, their column densities were the same: $\Sigma \simeq 10^3 \, M_\odot \, \text{pc}^{-2}$ at $r_{gc}=8 \, \text{kpc}$. In addition, it is natural to expect $P_s \propto r_{gc}^{-2}$ for such protocluster clumps embedded in larger (but subgalactic) star-forming clouds that were themselves surrounded by a diffuse medium virialized in a "background" isothermal potential well (Harris & Pudritz 1994). Together, these basic hypotheses imply $E_{b,}\text{gas} = 4.8 \times 10^{42} \, \text{erg} \,(M/M_\odot)^{1.5} \,(r_{gc}/8 \, \text{kpc})^{-0.5}$. Note that the $r_{gc}$ scaling is essentially that observed directly for Galactic globulars today, enabling a direct comparison of the (model) initial and final $E_{b}(M, r_{gc})$ relations in Fig. 2.

To explain the relative $E_{b}(M)$ normalizations in Fig. 2 requires quantitative modelling of the initial structure and feedback dynamics in the gaseous protoclusters. Meanwhile, the different slopes of the two relations are significant: The ratio of the initial energy of a gaseous clump to the final $E_{b}$ of a stellar cluster is a non-decreasing function of the cumulative star formation efficiency $\eta$; but this Figure shows that it is also an increasing function of cluster mass, and thus that $\eta$ was systematically higher in more massive protoclusters. The quantitative details of this dependence are also model-dependent (McLaughlin, in preparation),

Figure 2. Binding energy vs. mass for globular clusters (points and solid line; see McLaughlin 2000) and their gaseous progenitors (broken line) in the Galaxy. Total cluster luminosities are converted to masses by applying the constant mass-to-light ratio indicated.
but the inference on the qualitative behavior of $\eta$ is robust and presents a new constraint for theories of cluster formation. Once the behavior of $\eta$ as a function of initial gas mass is understood, progress will have been made in explaining the universal $\epsilon_{cl}$ of §2, and there will be further implications for other global properties of GCSs—such as their mass functions, which, contrary to current modelling (McLaughlin & Pudritz 1996; Elmegreen & Efremov 1997), can no longer simply be assumed proportional to those of their gaseous protoclusters.

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Discussion

G. Meurer: Concerning the two-orders-of-magnitude difference between $\epsilon_{\text{cl}}$ and the fraction of UV light in starbursts: One order of magnitude may be explainable by the gas content in starbursts.

McLaughlin: That does seem plausible (e.g., Zepf et al. 1999), although it should of course be checked in detail in every individual case. But the gas mass in starbursts really does have to enter as much more than a factor-of-ten effect if there is no boost in the cluster formation efficiency in starbursts vs. old galaxy halos. A real question remains as to whether or not that is the case.

G. Östlin: Since none of the fundamental properties of globular clusters depend on metallicity, including the core mass-to-light ratio which appears constant, I guess this requires them to have had a universal stellar IMF, independent of metallicity.

McLaughlin: I think that’s exactly right.