REVIEW

Massive star clusters in galaxies

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The ensemble of all star clusters in a galaxy constitutes its star cluster system. In this review, the focus of the discussion is on the ability of star clusters, particularly the systems of old massive globular clusters (GCs), to mark the early evolutionary history of galaxies. I review current themes and key findings in GC research, and highlight some of the outstanding questions that are emerging from recent work.

Keywords: globular clusters: general; galaxies: stellar content; galaxies: formation

1. Introduction

The observational evidence available to date indicates that a major star-forming epoch in a galaxy’s history will generate a new set of star clusters that accompanies its population of ‘field’ stars. Thus, it is physically meaningful to think of a subsystem of star clusters as consisting of all clusters formed in a given starburst, and to treat the clusters as a proxy for the stellar subpopulation formed in the same burst (see de Grijs (2010) and Larsen (2010) for more extensive treatments of cluster formation in starburst environments).

The huge advantage offered by star clusters is that they are easily bright enough to be measured individually within galaxies as distant as 100 Mpc and even beyond, and, in giant galaxies particularly, they can be found in large numbers (figure 1). We can then construct distribution functions of such key parameters as mass, age and heavy-element abundance (metallicity) for the clusters, instead of just the luminosity-weighted averages that we get from the unresolved field-star light.

The Milky Way star cluster system (our starting point for all such work and the ‘baseline’ comparison system for all other galaxies) separates out rather cleanly into the two classic subsystems: the open clusters (found throughout the disc and spiral arms along low-eccentricity orbits) and the globular clusters (GCs; inhabiting the galactic bulge and halo in a roughly isotropic distribution of orbits). In addition, the GCs are distinctly older than the open clusters (although with a small range of overlap around approx. 8–10 Gyr), as well as more massive and less enriched in heavy elements, indicating that they belonged to a brief early stage of rapid star formation and chemical enrichment. The open clusters, like

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the general population of disc field stars, are found at any age but over a more restricted range of metallicities, marking the more gradual ongoing growth of the galaxy’s disc.

But in even the nearest external galaxies (the Magellanic Clouds, M31 and the other Local Group galaxies), this convenient dichotomy disappears. The Clouds, for example, contain small numbers of classically old, massive, metal-poor GCs as well as many analogues of open clusters, but we also find numerous examples of high-mass, young clusters that probably resemble GCs as they would have been closer to their formation time. Investigations of star cluster systems in other galaxies reveal still richer varieties, to the stage where every part of the star cluster age/mass/metallicity three-parameter space is occupied.

For thorough reviews and perspectives on the earlier literature up to approximately 2005, interested readers should see Harris & Racine (1979), Harris (1991, 2001), Ashman & Zepf (1998) and Brodie & Strader (2006). The present article will concentrate on recent developments in GC system (GCS) studies, leading up to a list of currently challenging questions. This short and biased discussion unfortunately cannot do justice to the diversity and richness of approaches now underway, and (happily) it will be doomed to be quickly superseded by the rapid advance of both theory and data. Perhaps, the most important single implication of the work in this area, however, is that the old GCs represent a common thread in early galaxy evolution, dating back to the first star formation within the pre-galactic gas clouds.

2. Data versus theory: some perspective

Some perspective should be offered at this point about the links between models and observations. This field is at basis a branch of old stellar populations extended to the full range of galaxy types. GCS studies began as a strongly data-dominated subject, with most discoveries coming directly from photometric and
spectroscopic surveys that were guided primarily by the astrophysical intuition of the observers. Quantitative models tended to follow later. Some branches of astrophysics (e.g. Big-Bang cosmology, stellar structure, stellar dynamics) have clear mathematical foundations accompanied by small numbers of distinctive ‘parameters’ that can be invoked to design new observing programmes. This near-equal cooperation between models and data is not currently the situation here, and a genuine understanding of the formation and evolution of star cluster systems within their parent galaxies is a considerably more complex issue. It starts on the broad platform of the hierarchically merging galaxy-formation era, and continues with the operation of gas dynamics at all scales, from protogalaxies down to protostars, simultaneously with other key elements including galaxy mergers, satellite accretions and dynamical evolution of compact stellar systems. In the face of this complexity, making the transition from models that are ‘scenarios’ (even if basically accurate) to ones that are both quantitative and realistic in detail is a steep challenge. Nevertheless, with the rapid advance of high-performance computation and the ability to simulate these processes at a genuinely deep level, we can look forward to major progress on the theory front.

At least some key features of GCS formation have, however, been isolated. At one extreme lie the smallest dwarf galaxies that have shallow potential wells that can support only a brief initial starburst or else much slower, less dramatic star formation. These early, low-metallicity pre-galactic dwarfs were probably the formation sites of the metal-poor blue-sequence GCs (although also leaving behind an intriguing ‘specific-frequency problem’; see below) (Searle & Zinn 1978; Harris & Pudritz 1994; Burgarella et al. 2001; Beasley et al. 2002; Brodie & Strader 2006; Mashchenko et al. 2008). At the other extreme are the giant and supergiant ellipticals whose GCSs are almost certainly composite populations. They will have GCs originating from dissipational collapse with huge amounts of gas undergoing star formation spread over several episodes, dissipationless accretion of satellites coming in later with their own small populations of GCs and major merging of progenitor disc or elliptical galaxies, with various mixtures of stars and gas. How important each of these contributions will be for a given galaxy must be driven by its size, environment and the stochastically governed individual hierarchical-merging history. Major attempts to follow these processes simultaneously have been carried out for giant ellipticals in a semianalytic model (Beasley et al. 2003) and for the Milky Way in cosmological simulations (Bekki & Chiba 2001; Kravtsov & Gnedin 2005), but these are still exploratory and use prescriptive rules for star and cluster formation. However, syntheses of these approaches are developing (Bekki et al. 2008), and hydrodynamic simulations of the important cases of GC formation in major mergers and in pre-galactic dwarfs are approaching the dynamical range required to resolve individual clusters (Bournaud et al. 2008; Maschenko et al. 2008).

### 3. Metallicity distributions

A key and (fortunately) observationally prominent marker of evolution in a stellar population is its heavy-element abundance or metallicity. The increase in mean metallicity with time—driven by steady conversion of gas into stars and the cycle of stellar evolution and supernova-driven enrichment—is extremely rapid at the
earliest times when the gas fractions are highest. It also seems to be rapid in some of the most violent and shock-driven star-forming environments. The metallicity distribution function (MDF) is thus one of the most important directly observable tracers of this history.

A major discovery characterizing GCSs is that the whole MDF breaks into a strikingly bimodal form, with a metal-poor mode centred near [Fe/H](MP) ≃ −1.5 dex and a metal-rich mode centred near [Fe/H](MR) ≃ −0.4 dex. A graphic illustration of this two-subpopulation division, as it is most frequently measured, is shown in figure 2. Broadband photometric indices such as in figure 2 for GCs older than approximately 5 Gyr become quite insensitive to age and thus the colour reflects the cluster heavy-element abundance surprisingly well. By convention, the metal-poor GCs are often called the blue sequence while the metal-richer ones are the red sequence. The translation from GC colour to metallicity (which is monotonic, but may be nonlinear) is ultimately established from spectroscopic abundance measurements, which have now been done in several galaxies (see the work by Brodie & Huchra 1990; Cohen et al. 1998, 2003; Kissler-Patig et al. 1998; Barmby et al. 2000; Perrett et al. 2002; Puzia et al. 2005; Cenarro et al. 2007; Strader et al. 2007; Woodley et al. 2010; and the fundamental data for the Milky Way clusters).
These two major GC sequences were first identified definitively in the Milky Way with the work of Zinn (1985), who demonstrated that the two subpopulations had distinct kinematic systemics and spatial distributions as well. The metal-poor cluster subsystem occupies a more extended spatial distribution through the bulge and halo and is kinematically more like an isotropic orbital distribution, while the metal-rich subsystem defines a more centrally concentrated spatial distribution and kinematically contains a higher component of ordered, rotational motion somewhat resembling the field stars in the galactic ‘thick disc’ or bulge.

Dozens of observational papers establishing the bimodal MDFs in other galaxies exist, but key examples include Zepf & Ashman (1993), Zepf et al. (1995), Whitmore et al. (1995), Geisler et al. (1996), Gebhardt & Kissler-Patig (1999), Neilsen & Tsvetanov (1999), Larsen et al. (2001), Kundu & Whitmore (2001), Peng et al. (2006) and Harris (2009a,b). The factor-of-ten difference in heavy-element abundance between an average metal-poor and a metal-rich GC becomes more sharply defined if more metallicity-sensitive colour indices are used (see Harris et al. 1992, 2004; Geisler et al. 1996; Rhode et al. 2005; Peng et al. 2006; Spitler et al. 2008a; Harris 2009a,b). Direct spectroscopic abundance measurements are best, although these entail far costlier and more resource-intensive data acquisition. But the clear advantage of photometric samples is that reliable first-order MDFs can be readily obtained for large numbers of galaxies, offering us the ability to track statistical trends across all types of galaxies and environments. Bimodality is now seen so widely that any clear deviations from it within an old GCS would now be regarded as anomalous.

If bimodality is the major first-order feature of the MDF, there are now three second-order trends providing intriguing additional links to the early enrichment histories of both the host galaxies and the clusters themselves.

(i) Mean metallicity and dispersion versus galaxy size. The blue and red sequences individually appear at much the same mean metallicity in all galaxies from giants down to dwarfs, and from spirals to ellipticals. In addition, the intrinsic dispersion of each sequence (i.e. the rms range in the cluster-to-cluster differences in metallicity) is roughly constant at $\sigma_{\text{Fe/H}}(\text{blue}) \simeq 0.30$ dex and $\sigma_{\text{Fe/H}}(\text{red}) \simeq 0.45$ dex. The intrinsic dispersion must represent the overall growth of enrichment during a major star-forming period: a cluster forming slightly later in the sequence will start with a larger amount of pre-enrichment in its parent giant molecular cloud. However, a more subtle trend is that the mean metallicity of each sequence increases steadily with host-galaxy luminosity. Expressed in terms of heavy-element abundance $Z$, the scaling relation is $Z \sim L^{0.24\pm0.05}$ (Forbes et al. 1997; Larsen et al. 2001; Strader et al. 2004; Brodie & Strader 2006; Peng et al. 2006).

In qualitative terms, this mean-metallicity scaling indicates that a random GC (either metal-poor or metal-rich) drawn from a present-day dwarf galaxy has a lower enrichment than one drawn from a giant, thus arguing against pure major merger or dissipationless accretion scenarios in which, for example, the blue-sequence clusters now present within a giant galaxy all formed within smaller progenitors later accreted into the bigger central potential. A caveat to this view (Brodie & Strader 2006) is that an isolated pre-galactic dwarf should have a different and more truncated enrichment history than its counterparts lying within the deeper large-scale potential well of an emerging giant elliptical. The
key hint from the data, however, is that the global environment of the galaxy (on scales of approx. 100 kpc) has influenced the local formation conditions of its star clusters (on scales of a few pc).

(ii) The mass/metallicity relation (MMR). An unexpected finding of new high-precision photometric surveys of GCSs in giant galaxies is a correlation between the mean colours of the blue-sequence GCs and their luminosities (e.g. Harris et al. 2006; Mieske et al. 2006; Spitler et al. 2006; Strader et al. 2006; Forte et al. 2007; Cockcroft et al. 2009; Harris 2009a, b; Peng et al. 2009). Effectively, the blue GCs become progressively more heavy-element enriched at higher cluster mass. The exact form of the correlation was a matter of debate in the first round of papers, but a consensus has been emerging around two conclusions: (i) the blue sequence is essentially vertical for the less massive clusters in the range \( M < 5 \times 10^5 \, M_\odot \), that is, \( Z \sim L^0 \) for low-mass GCs. But at progressively higher \( L \) (extending up to the most luminous GCs known at \( 10^7 \, L_\odot \)), the blue sequence bends towards redder colours, eventually following a slope near \( Z \sim L^{0.3} \) at its top end (Harris 2009a, b; Peng et al. 2009). (ii) No such trend has been found along the red sequence, which is indistinguishable from vertical in all systems studied so far. Detecting this MMR clearly requires internally precise photometry and very large GC samples because clusters above the approximately \( 10^6 \, M_\odot \) level (where the MMR becomes most noticeable) are rare and the changes in mean colour are not large (figure 2).

The MMR is, at this point, thought to be the result of some form of self-enrichment of massive clusters during their formation period (Strader & Smith 2008; Bailin & Harris 2009). A sufficiently massive and dense protocluster (approx. \( 10^7 \, M_\odot \) of gas within a 1 pc protocluster core) can provide a sufficiently deep potential well and enough dense gas to hold back a high fraction of the enriched supernova ejecta from the first round of massive stars within the protocluster, which can then enrich the still-forming lower main-sequence stars. For this mechanism to work, the entire starburst needs to take 20–30 Myr to complete. For the highest-mass GCs, the net enrichment over and above its pre-enriched metallicity will be \( \Delta Z \simeq 0.05 \, Z_\odot \), large enough to double its initial \( Z_{\text{init}} \approx 0.04 \, Z_\odot \) along the blue sequence. But the lower mass clusters cannot be significantly self-enriched because the supernova heating of the surrounding protocluster ends up ejecting almost all gas not converted to stars. Interestingly, this model predicts that the phenomenon should affect the metal-rich GC sequence too, but it would be almost undetectable on the red sequence because the incremental \( \Delta Z \) is always small relative to their pre-enriched level, \( Z_{\text{init}} \approx 0.4 \, Z_\odot \).

(iii) Metallicity gradients. The mean metallicity of the entire GCS in large galaxies has long been known to decrease outward in the halo. However, most of this global gradient is actually caused by the changing proportions of red versus blue clusters with changing galactocentric distance, \( R_{gc} \), that is, it is the result of a population gradient (e.g. Zinn 1985; Harris et al. 1992, 2006; Geisler et al. 1996; Rhode & Zepf 2004). One of the more well-defined but not atypical examples is shown in figure 3 for the Virgo giant elliptical M87 (Tamura et al. 2006; Harris 2009b). Notably, the metal-rich GCs follow a spatial distribution that mimics fairly closely the similarly metal-rich spheroid light of the host galaxy, suggesting that they formed together. The same view is supported by the details of the MDF for both clusters and field-halo stars (see subsequent text). By contrast,
Figure 3. (a) Radial profile for the GCS in the Virgo giant elliptical M87 (Harris 2009b). The metal-poor and metal-rich clusters are shown as the solid dots and open triangles, respectively. The red clusters form a more centrally concentrated subsystem of the galaxy spheroid. (b) Distribution of GC colour \((B-I)_0\) versus galactocentric distance for the luminous GCs in six supergiant ellipticals. The best-fit power-law curves for the red and blue sequences are shown as the dashed lines, corresponding to a metallicity scaling of \(Z \sim R^{-0.1}\).

the shallower spatial distribution of the blue GCs more closely resembles that of the isothermal dark-matter potential well, or is intermediate between the dark matter and the halo light, consistent with the interpretation that the blue GCs formed at quite an early stage.

But at a finer level, true metallicity gradients can be found within each of the two subpopulations. That is, the red and blue GCs show an intrinsic decrease in mean metallicity with increasing \(R_{gc}\), scaling as \(Z \sim \frac{1}{R_{gc}^{(0.1-0.2)}}\) (see figure 3b and Geisler et al. 1996; Lee et al. 2008; Harris 2009a, b). In the hierarchical-merging picture, the mean GC metallicity would reflect the depth of the larger scale potential well within which it was formed, being able to reach a higher level of pre-enrichment deeper into the galaxy centre. Later accretions of dwarf satellites, which have more metal-poor GCs, would add to the population predominantly in the outskirts of the halo. A potential but important complication is that later major mergers after formation may have diluted the initial metallicity gradient (or, if the merger brought in a very large amount of gas, it may have helped rebuild the gradient for the metal-richer clusters only).

4. Age distributions and galaxy formation

The Milky Way and its nearby satellites (the Magellanic Clouds, Sagittarius and Fornax) contain the only populations of GCs for which truly fundamental age calibrations can be achieved, based on isochrone fitting to the deep, unevolved
Figure 4. (a) Results for spectroscopically determined ages and abundances of the GCs in the nearby giant elliptical galaxy NGC 5128; (i) $\chi^2 = 0.74$; (ii) $\chi^2_{\text{uni}} = 1.29$, $\chi^2_{\text{tri}} = 1.41$ and $\chi^2_{\text{bi}} = 1.43$; (iii) $\chi^2_{\text{uni}} = 0.59$ and $\chi^2_{\text{bi}} = 0.79$. (b) Ages and abundances for Milky Way GCs, determined with the same techniques. The fitted lines show various unimodal and bimodal Gaussian solutions to the age and abundance distributions in each galaxy. (i) $\chi^2 = 0.89$, (ii) 1.13 and (iii) 1.27. (All data from Woodley et al. 2010.)

main sequence and even the white-dwarf sequence. Published work (e.g. Gratton et al. 2003; De Angeli et al. 2005; Hansen et al. 2007; Marín-Franch et al. 2009; among many others) indicates that the absolute age of the metal-poor clusters is near 13 Gyr and shows a cluster-to-cluster dispersion that may be as low as $\pm 0.5$ Gyr, confirming their classic status as among the first stellar structures to have formed in the galaxy. The mean age for the metal-richer subsystem is perhaps 2 Gyr younger than the extremely old, metal-poor subsystem, and exhibits a higher cluster-to-cluster age scatter, near $\pm 2$ Gyr rms.

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Direct age measurements for GCs in other, more distant systems are extremely important but inevitably less precise. A method of attack that has gained some valuable ground in the past decade has been the use of spectroscopic line-strength parameters from the integrated light of GCs, which are sensitive to different combinations of age, $\tau$, metallicity, [Fe/H], and $\alpha$-abundance ratio, [$\alpha$/Fe]. Because the Balmer lines are affected strongly by the faint but numerous stars near the main-sequence turnoff, they are sensitive to age, while the many different metal lines (Fe, Ca, Mg, etc.) are more exclusively influenced by metallicity. From high signal-to-noise ratio spectra at moderate resolution, age determinations precise to $\pm 2$ Gyr (for the ‘old’ age regime, $\tau \sim 10$ Gyr) can be achieved. Key case studies can be found in Proctor et al. (2004), Puzia et al. (2005), Pierce et al. (2006), Beasley et al. (2008) and Woodley et al. (2010), among several others. A recent sample for NGC 5128 is shown in figure 4. Direct comparison with the Milky Way clusters indicates that the NGC 5128 GCs exhibit a comparable $\alpha$-abundance distribution, along with the familiar bimodal MDF. However, the age distribution for the NGC 5128 GCS clearly extends to younger ages, with a hint of major starbursts having occurred at ages of approximately 11, 9 and 5 Gyr. By contrast, on the same age-calibration scale, the Milky Way GCs range exclusively from 10 to 13 Gyr. Roughly similar age patterns show up in other large ellipticals (see the references cited above). Although the absolute age scale for these spectroscopic-index programmes is still a work in progress, the data so far strongly confirm that large ellipticals are composite systems which assembled in steps from very high redshift down to $z \sim 1 - 2$.

5. Cluster sizes and the fundamental plane

A surprisingly effective outcome of the Hubble Space Telescope (HST) imaging programmes for nearby galaxies and their GCSs has been the ability to measure accurately the scale sizes of the GCs, i.e. their effective or half-light radii, $r_{\text{eff}}$ or $r_h$. This is a dynamically valuable quantity because it stays nearly invariant over many internal relaxation times and thus is one of the best signatures we have of the linear size of the cluster shortly after it formed its stars and ejected the remaining protocluster gas. For galaxies within the Local Group, the structure of the cluster can be resolved to within its core radius, $r_c$ (Barmby et al. 2007) and rather complete profile fitting is readily possible. At increasing distances, the linear size of a GC gradually shrinks relative to the 0.1" HST resolution, but the crucial scale radius $r_h$ can be accurately measured for galaxies out to 50 Mpc (major databases of this type are in Jordán et al. (2005) and Harris (2009a)) by appropriate convolution with the stellar point-spread function.

Four representative sets of GC scale-radius data are shown in figure 5: GCs in the supergiant elliptical M87 (Madrid et al. 2009), the giant Sa disc galaxy M104 (Harris et al. 2009), a compendium of GCs in nearby dwarf ellipticals (dEs; Georgiev et al. 2009) and the Milky Way clusters (data from Harris 1996). The fundamental similarities among these very different galaxies are striking (e.g. Jordán et al. (2005), who explore their potential as a ‘standard ruler’). The asymmetric tail to larger $r_h$ is the most noticeable second-order difference. Clusters with $r_h \gtrsim 5$ pc are found predominantly in the dwarf galaxies and (for the Milky Way) among the lower mass clusters in the outskirts of the halo.
Figure 5. (a) Effective (half-light) radii, $r_h$, for old GCs in four systems: (i) the giant elliptical M87, (ii) the giant Sa M104, (iii) a combination of nearby dwarf galaxies and (iv) the Milky Way. (b) Log $r_h$ versus cluster luminosity for GCs in three massive disc galaxies: the Milky Way (large filled circles), M31 (triangles) and M104 (small crosses). The median size, $r_h = 2.3$ pc, is shown as the dashed line.

apparently reflecting their gentler tidal-field environment from birth. Da Costa et al. (2009) suggest that the distribution may be bimodal, with a secondary mode at $r_h \geq 8$ pc found in the dwarfs. The intrinsic shape of the size distribution has been suggested to result ultimately from a stochastic range in star-formation efficiencies starting from a rather narrow range of initial protocluster sizes (Harris et al. 2009), followed by a longer phase of dynamical evolution that shapes both the present-day size and mass distributions (e.g. Fall & Rees 1977; Gieles & Baumgardt 2008).

More quantitatively, GC structural parameters have been used to define a fundamental plane analogous to that for elliptical galaxies (Djorgovski 1995). Their various structural properties are in fact so tightly correlated that their structures are almost completely specified by just two parameters, mass and (secondarily) central concentration (McLaughlin 2000). A simple version of this manifold is shown in figure 5b, where GC scale size is plotted versus luminosity for three massive disc galaxies. GCs do not follow the scaling relation $r_{\text{eff}} \sim L^{1/2}$ that typifies only slightly more massive, compact stellar systems such as dE nuclei and ultracompact dwarf (UCD) galaxies (e.g. Evstigneeva et al. 2008; Mieske et al. 2008). Instead, for GCs less massive than $\sim 10^6 M_\odot$, we find $r_{\text{eff}} \sim L^0$. A long-standing question has been whether or not the GCs are truly distinct stellar systems or whether there is any kind of ‘bridge’ connecting them to the lower end of the dE/UCD manifold. The recent evidence, drawn from galaxies with the
richest GC populations in which we can find significant numbers of high-mass clusters, is that the radii start to increase for \( M \geq 10^6 \, M_\odot \) and may merge fairly seamlessly onto that upper manifold.

6. The specific-frequency ‘problems’ and formation issues

GCSs that we see today in the haloes of galaxies of all types have typical masses of \( 10^5 \, M_\odot \), but the mass of their original protocluster is likely to have been substantially larger (and more so at higher mass). The raw star-formation efficiency within the protocluster is expected to be approximately 30 per cent. After formation, it undergoes continual mass loss dominated (at early times) by supernovae and stellar winds from its massive stars, and at later times by stellar evaporation and tidal truncation, reducing its total mass after 12 Gyr by another factor of 2 or more depending on the initial mass (Baumgardt & Makino 2003; Baumgardt & Kroupa 2007; McLaughlin & Fall 2008). At a broader galaxy-wide level, the high-resolution simulation of Bournaud et al. (2008) indicates that about 4 per cent of the gas in a relatively strong major merger is converted into small, dense clouds that can be plausibly identified as protoglobular clusters. Combining these arguments then suggests that present-day galaxy haloes should have \( \lesssim 0.5 \) per cent of their stellar mass in the GCS. For comparison, the most thorough observational estimates of the mass fraction \( M_{\text{GCS}}/M_{\text{bary}} \) (McLaughlin 1999; Peng et al. 2008; Spitler et al. 2008b) place \( M_{\text{GCS}} \) in the range 0.1–1\% of the total baryonic mass of a large galaxy, correlating weakly with the luminosity of the galaxy itself and also accounting for any non-stellar mass in X-ray halo gas. For dwarf galaxies \( \lesssim 10^8 \, M_\odot \), this mass fraction scatters much more, ranging from zero to above 3 per cent. Spitler & Forbes (2009) argue that \( M_{\text{GCS}} \) may be most tightly determined by the total dark-matter halo mass of the parent galaxy except, again, for the smallest dwarfs.

Recent simulations show that protoclusters of the right mass scale to resemble GCs will form both in the low-metallicity environment of pre-galactic dwarfs (Mashchenko et al. 2008) and in gas-rich mergers of large disc galaxies (Bournaud et al. 2008). But all of the contemporary analyses lead to the conclusion that it takes a very large reservoir of gas to make a typical GC. The actual conversion efficiency (essentially, the ratio of GC protocluster mass to its local host giant molecular cloud mass) may depend on merger shock velocities, metallicities and other environmental factors, and needs to be much better understood than it is now.

Specific frequency \( S_N \) is the number of GCs per unit galaxy luminosity and is the most obvious observational proxy for GC formation efficiency. Much of the original puzzle over the order-of-magnitude differences in \( S_N \) between, say, spirals and ellipticals, or cD ellipticals versus field ellipticals (e.g. Harris 2001), has been alleviated by focusing on the mass ratio instead (see above). The possibility that most of the metal-rich clusters in elliptical galaxies formed through major mergers (Ashman & Zepf 1992) does not, by itself, solve the original ‘\( S_N \) problem’ because such large amounts of incoming gas are needed to make the thousands of GCs in giant ellipticals at any plausible formation efficiency that this version of their origin becomes similar to basic hierarchical merging (see Harris 2001). The
\textit{SN} values calculated separately for the red and blue GCs vary systematically and non-linearly with galaxy luminosity, a pattern thoroughly discussed by Peng \textit{et al.} (2008).

A newer ‘specific-frequency problem’ is exemplified in figure 6. The nearby giant elliptical system NGC 5128 offers a rare opportunity to compare the MDFs of the GCs and the halo red-giant stars in the same galaxy. Our zeroth-order assumption is that a major formation episode in a galaxy’s history should produce GCs in direct proportion to the amount of gas. If so, the MDFs of both types of stellar populations should have the same shape, being merely scaled versions of each other. (But this is plainly not the case (figure 6): there are about five times fewer metal-poor halo stars per unit GC at the same metallicity than metal-rich halo stars.)

The analyses for this and other galaxies (e.g. Forte \textit{et al.} 2005) show that metal-rich GCs match the mean metallicity and dispersion of the halo giants well enough to further support the default interpretation that they formed along with the bulk of the galaxy’s spheroid. But where are the many metal-poor stars that should go along with the metal-poor clusters? Interestingly, similarly high \textit{SN} values can be found in some low-luminosity dEs, whose GCs are predominantly metal-poor (Peng \textit{et al.} 2008).

One possible solution is that the metal-poor halo stars are present, but they occupy a much shallower spatial distribution than the metal-rich spheroid, just as the low-metallicity clusters form a spatially more extended subsystem than the metal-rich clusters. The metal-poor field halo would become dominant only at larger galactocentric distances than have normally been searched (see Harris \textit{et al.} (2007) for some tantalizing evidence along those lines). Another is a timing argument: if the massive, dense proto-clusters formed earliest in the pre-galactic clouds, and if later star formation was partially truncated (perhaps by the epoch of reionization), then \textit{SN} (blue) would end up artificially high (Harris & Harris 2002). A step towards a more quantitative interpretation has been developed by Peng \textit{et al.} (2008), who argue that the GC formation rate will scale with both
the star-formation rate and the star-formation-rate density, thus boosting cluster formation at high redshifts. Much remains to be discovered about the determining conditions of GC formation.

7. Questions, puzzles and further directions

The study of GC populations in galaxies provides a unique observational window on galaxy formation. A shortlist of the questions that have emerged from recent work would certainly include the following:

(i) What is the physical cause of bimodality? It does not automatically emerge from current semianalytic or cosmological simulations without deliberately inserting an external truncation mechanism such as reionization (Beasley et al. 2002; Kravtsov & Gnedin 2005). Was the formation of intermediate-metallicity clusters truncated near $z \sim 5$, in the same way in all major galaxies? Or were those clusters present but somehow biased towards smaller masses, which would then have been removed more easily by dynamical evolution?

(ii) Why was the formation of metal-poor, blue GCs so efficient relative to the ‘normal’, red GCs? Do the outermost parts of galaxy haloes possess large numbers of metal-poor stars? More generally, what features of the gas dynamics and composition inside a giant molecular cloud determine the formation efficiency of massive clusters?

(iii) The formation of a giant elliptical galaxy may have finished with a few major, gas-rich mergers, each of which generated metal-rich clusters. Thus, the red GC ‘sequence’ is, in itself, probably a composite population. Is there a way to deconvolve the red sequence into its age/metallicity components?

(iv) ‘Field’ ellipticals typically have low specific frequencies and are the most likely to have formed from late major mergers. But these are very incompletely surveyed in comparison with the GC-rich ellipticals in the Virgo, Fornax and Abell clusters. Do they show the same features of bimodality, the same GC luminosity functions and the same proportions of red/blue clusters as the rich ellipticals?

(v) GCs more massive than approximately $10^6 M_\odot$ belong to an intriguing ‘transition region’ characterized by an MMR, increasing scale size, higher mass-to-light ratios and (as we see in massive Milky Way GCs) multiple internal stellar populations. What drives these systematic changes at the high-mass end of the GC sequence? Cluster–cluster mergers? Increasing importance of dark matter? Can all compact stellar systems, from GCs through UCDs and elliptical galaxies, eventually be placed onto a single astrophysical sequence?

(vi) What is the total evolution of a massive star cluster from birth to death? A comprehensive evolutionary model needs to include the gas dynamics of its formation within a giant molecular cloud, early rapid gas-mass loss, ongoing internal dynamical evolution, slower secular evolution including the effects of the external tidal field and eventual dissolution into the field. Pieces of these steps are understood, sometimes in much detail, but a comprehensive end-to-end story still awaits assembly.
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