Formation of Globular Clusters in Merging Galaxies

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Abstract. Collisions and mergers of gas-rich galaxies trigger bursts of star and cluster formation. Of the thousands of clusters typically formed during a major merger, only the most massive and compact survive for gigayears as globular clusters (GCs). In \( \lesssim 1 \) Gyr old merger remnants, these ‘second-generation’ GCs appear by the hundreds as young halo clusters of \( \sim \) solar metallicity. Their likely descendants, metal-rich GCs of intermediate age (2 – 5 Gyr), have recently been found in \( \sim 10 \) E galaxies, where they appear as slightly overluminous red GCs with a still power-law-like luminosity function. Their color and radial distributions suggest that they evolve into the red metal-rich GCs observed in old ellipticals. There is good evidence that second-generation GCs form from giant molecular clouds shocked by the rapid pressure increase in merger-induced starbursts. This mechanism supports the view that the universal pressure increase during cosmological reionization may have triggered the formation of the metal-poor globulars observed in galaxies of all types.

1. Homage to Ivan King

Ivan King was my revered teacher. I owe him a lot, including an interest in globular clusters. Into my copy of his textbook The Universe Unfolding (1976), he wrote the dedication: “Make as much of this obsolete as you can, François! Best wishes, Ivan.” In this spirit I put forth the hypothesis that major mergers of gas-rich spirals form not only ellipticals, but also new globular clusters within them (Schweizer 1987). I cherish Ivan’s later comment on this hypothesis: “When Schweizer suggested resolving the \( S_N \) problem by making globular clusters in mergers, I thought it was ridiculous. But now in the HST observations of NGC 1275 we seem to see it actually happening” (King 1993).

Always quick to grasp major issues, Ivan challenged Alar Toomre at the Yale Conference as follows (King 1977): “You showed us 10 merging pairs [of galaxies] and then asked us to look for, or at least accept the existence of, 500 remnants from so long ago that they no longer bear the ‘made by Toomre’ label. I would be much more impressed if you showed us the 20 or 30 systems in the box immediately adjacent in your histogram. What do these merged pairs look like in their next few galactic years?”

As I hope to show in the present review, the descendants of major disk–disk mergers—i.e., ellipticals with globular clusters of intermediate age—are now being found in growing numbers.
2. Cluster Formation in Ongoing Mergers

Collisions and mergers of gas-rich spirals trigger bursts of intense star and cluster formation. Some well-known examples of ongoing mergers with spectacular systems of young clusters are NGC 4038/39 (Whitmore & Schweizer 1995; Whitmore et al. 1999), NGC 3256 (Zepf et al. 1999), and NGC 6052 (= Mrk 297, Holtzman et al. 1996). Although such mergers form star clusters by the thousands, it is currently difficult to predict what fraction of the clusters will survive as globular clusters (hereafter GC). Presumably only the more massive and compact clusters will survive for several Gyr, while many more fragile clusters and associations will disperse within a few internal crossing times. Nevertheless, several important results have emerged from Hubble Space Telescope (HST) studies of the above systems, and especially of NGC 4038/39 (Fig. 1): (1) Star clusters tend to form in regions of high gas density and are, therefore, clustered themselves; typically 10–20 young clusters belong to a complex previously identified from the ground as a giant H II region. (2) To a good approximation the cluster luminosity function is a power law, $\phi(L)dL \propto L^{-\alpha}dL$, with $1.7 \lesssim \alpha \lesssim 2.1$ and no evidence of any turnover at fainter magnitudes. (3) The most luminous clusters clearly show properties to be expected of massive young GCs and appear to display signs of structural evolution as a function of their age.

As an example of such evolution, Fig. 1b shows the radial-brightness profiles of three massive clusters in NGC 4038/39: Knot S and #430 are both very young (7 and 11 Myr) and display pure power-law envelopes, while the older cluster #225 (~500 Myr) shows both a larger core and an envelope with a distinct tidal cutoff. This suggests that young clusters are born with power-law envelopes that then get truncated by external tidal forces.

The power-law shape of the luminosity function appears to be a universal property of young cluster systems in starburst galaxies, irrespective of the exact cause of the burst (e.g., Meurer et al. 1995). The similarities between this power
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3. Globular Clusters in Young Merger Remnants

Studying GCs in young (0.3–1 Gyr) merger remnants offers two main advantages: (1) Dust obscuration is less of a problem than in ongoing mergers, and (2) most compact bright sources are true globular clusters. The second fact follows from the clusters’ measured half-light radii and ages. These ages typically exceed 100 Myr, or \( \sim 25–50 \) internal cluster-crossing times \( t_{\text{cr}} \), and thus indicate that such clusters are gravitationally bound. In contrast, most clusters in ongoing mergers like NGC 4038/39 and NGC 3256 are \( \lesssim 30 \) Myr or \( \lesssim 10 t_{\text{cr}} \) old and may eventually disperse. Therefore, the time lapse between the peak of cluster formation and the completion of a merger helps separate the wheat from the chaff.

Globular-cluster systems have been studied with HST in several young merger remnants, including NGC 1275 (Carlson et al. 1998), NGC 3597 (Carlson et al. 1999), NGC 3921 (Schweizer et al. 1996), and NGC 7252 (Miller et al. 1997). Each of these remnants hosts about \( 10^2 – 10^3 \) compact sources that appear to be luminous young GCs. Age dating based on broad-band photometry shows that the majority of these globulars formed in a relatively short, 100–200 Myr time span \textit{during} each merger. The young GCs appear strongly concentrated toward their host galaxies’ centers, half of them lying typically within \( \lesssim 5 \) kpc from the nucleus. In addition to its 102 candidate GCs, NGC 3921 (Fig. 2a) also hosts about 50 fuzzier objects that are likely stellar associations. These
Figure 3. (a) (left) H$\beta$ – [MgFe] diagram for two GCs in NGC 7252 (Schweizer & Seitzer 1998), and (b) (right) H$\alpha$ – Ca-triplet diagram for three GCs in NGC 1316 (Goudfrooij et al. 2001a). The NGC 7252 clusters are 550 ± 50 Myr old, the NGC 1316 clusters 3.0 ± 0.5 Gyr. Note that both sets of clusters have near-solar metallicities.

associations have colors ranging from relatively blue to quite red and may be in the process of dispersing. Interestingly, only three of these fuzzy objects lie within the central 5 kpc, presumably because most associations were too fragile to survive the intense churning near the merger’s center.

The GC system of NGC 7252 (Fig. 2b) has been studied in some detail. Spectroscopy shows that seven of eight young GCs feature strong Balmer absorption lines (EW[H$\beta$] = 6 – 13 Å) indicative of a main-sequence turnoff dominated by A-type stars. The GCs’ age distribution appears very peaked, with six clusters having ages in the narrow range 400 – 600 Myr (Schweizer & Seitzer 1998). Infrared photometry in the K-band confirms that most young globulars in the halo of NGC 7252 are presently in the AGB phase-transition stage, which lasts from ∼200 Myr to 1 Gyr (Maraston et al. 2001).

The metallicity of these young halo GCs is near solar. Figure 3a shows a H$\beta$ – [MgFe] diagram for the two globulars NGC 7252:W3 and W6 (data points), from which [Z] = 0.00 ± 0.08 for W3 and +0.10 ± 0.17 for W6. A fascinating object is S101, a freshly born halo cluster located in an H II region that is falling back into NGC 7252 from a tidal tail (with $\Delta v_{\text{rad}} = -241$ km s$^{-1}$) and has a metallicity of [Z] = −0.12±0.05. This cluster, located at a projected distance of 15 kpc, suggests that young GCs can form with considerable time delays when tidally ejected gas crashes back into a remnant.

The line-of-sight velocity dispersion of the eight spectroscopically observed GCs in NGC 7252 is 140 ± 35 km s$^{-1}$, leaving little doubt that these clusters belong to a halo population. HST photometry shows that there are ∼300 similar young GCs in the halo, in addition to the old GCs that likely belonged to the halos of the two input spirals. Hence, the color distribution of the GCs is bimodal, with the main peak at $(V - I)_0 \approx 0.65$ due to the clusters formed 400–600 Myr ago and the secondary peak at $(V - I)_0 \approx 0.95$ likely due to the brightest of the old metal-poor GCs (Miller et al. 1997).
In short, the merger of two gas-rich spirals in NGC 7252 has led to a young remnant with a bimodal population of halo globulars. Besides the universal old metal-poor GCs the halo also features many second-generation GCs that are young and metal-rich. The situation appears to be similar in the young remnants NGC 3597 and NGC 3921, and perhaps also in NGC 1275. The many properties that these remnants share with ellipticals suggest not only that the remnants are present-day protoellipticals (e.g., Schweizer 1998), but also that E and S0 galaxies with bimodal cluster distributions may have formed their second-generation metal-rich GCs in a similar manner. Interestingly, the ratio of young to old GCs is $\gtrsim 0.4$ in NGC 3921 (Schweizer et al. 1996) and $\sim 0.7$ in NGC 7252 (Miller et al. 1997). These ratios compare well with the mean ratio of $\sim 0.6$ for metal-rich/metal-poor GCs observed in normal giant ellipticals.

4. Globular Clusters in Intermediate-Age Merger Remnants

If indeed E and S0 galaxies with bimodal cluster distributions formed through mergers similar to those described above, we should be able to find such galaxies with second-generation GCs of intermediate age (1–7 Gyr). These galaxies could help us trace the evolution of second-generation GC systems from young through intermediate to old age. Potential tracers of such evolution are, e.g., the GC color distribution, luminosity function, and radial distribution.

There is now evidence for the presence of intermediate-age GCs in about ten elliptical galaxies, including NGC 1316, 5128, 1700, 3610, 4365, and 6702. The best case is NGC 1316, where spectra of GCs support the intermediate ages found from broad-band photometry (Goudfrooij et al. 2001a, b). Figure 3b shows measured equivalent widths of H$\alpha$ for three bright GCs plotted versus the equivalent width of the Ca II triplet. From the superposed model grid one can see that all three GCs are about $3.0 \pm 0.5$ Gyr old and have close to solar abundances. Their ages agree with the ages inferred from $BV$ and $JHK$ photometry for 50–60% of a sample of $\sim 300$ GCs in this galaxy. Therefore, the red peak of the bimodal color distribution in NGC 1316 clearly contains GCs of intermediate age, and this merger remnant provides a valuable evolutionary link between young remnants like NGC 7252 and old ellipticals with bimodal cluster distributions.

For the other galaxies with candidate intermediate-age GCs we have to rely on broad-band colors. Model simulations of bimodal GC populations with second-generation clusters of solar metallicity predict what we can expect to observe at different ages (Whitmore et al. 1997, esp. Fig. 15): At 0.5 Gyr the second-generation GCs should appear both bluer and $\sim 2$ mag brighter than the old metal-poor GCs, as is observed in the young remnants discussed above. Then the aging second-generation GCs become redder. At 1.0–1.5 Gyr they reach about the same $V - I$ color as old GCs, but are still $\sim 1.5$ mag brighter. At 3 Gyr they are already distinctly redder than the old GCs but still 0.5–1 mag brighter, while at $\gtrsim 10$ Gyr they appear both redder and slightly fainter. Figure 4 illustrates that this predicted crossover of GC colors does indeed occur. Shown are the color distributions of clusters in seven galaxies, with second-generation GCs ranging from very young and blue in The Antennae to old and red in M87. Whereas the general evolution from blue to red colors for second-generation
GCs has been known for some time, the more detailed transition shown in the right-hand panels of Fig. 4 is new. The new data for NGC 1316 (Goudfrooij et al. 2001b), NGC 3610 (Whitmore et al. 2002), and NGC 1700 (Brown et al. 2000) diminish the gap in known cluster ages from 0.5 – 10+ Gyr previously to a current ∼0.5 – 3 Gyr.

A promising new method for finding more E + S0 galaxies with intermediate-age globulars is to break, or at least diminish, the age–metallicity degeneracy by supplementing HST photometry in $V I$ with ground-based photometry in the $K$ band. Applying this method to NGC 4365 (E3), Puzia et al. (2002) find a significant population of very metal-rich GCs of intermediate age in addition to old metal-poor and old metal-rich populations.

The luminosity function (LF) of second-generation GCs is another potential tracer of systemic evolution. The transition from the power-law form observed in young cluster systems to the log-normal form observed in old GC systems has been predicted theoretically by Fall & Zhang (2001). It is a consequence of the preferential disruption of low-mass clusters by various mechanisms, of which the main one is internal two-body relaxation and evaporation. The resulting erosion of the low-mass end should be evident in the observed LFs of second-generation GC systems that form an age sequence.

Striking differences between the LFs of red, metal-rich GCs and blue, metal-poor GCs have indeed been found in two bona fide ellipticals: NGC 1316 and NGC 3610. Both galaxies show fine structure indicative of mergers involving disks during the past few Gyr. Figure 5 compares the observed LFs of the blue $(0.8 \leq V - I \leq 1.02)$ and red $(1.02 < V - I \leq 1.3)$ GCs in NGC 3610. Whereas the LF of the blue clusters is nearly lognormal, as expected for old GCs, that of the red cluster is well approximated by a power law of index $-1.78 \pm 0.05$.
Figure 5. Luminosity functions of blue and red GCs in NGC 3610. Half-completeness limits (vertical dashed) mark boundary up to which the LFs can be trusted. Shaded areas mark background-corrected LFs, dotted lines uncorrected LFs. Notice the nearly lognormal shape of LF for blue GCs and power-law shape for red GCs (Whitmore et al. 2002).

(Whitmore et al. 2002). Thus, it supports the notion that many of the red GCs are not ancient, but formed relatively recently. The turnover predicted by Fall & Zhang’s models for 3–4 Gyr old clusters is presently not detected, perhaps because it lies near the 50% completeness limit. Therefore, an effort is under way to obtain new, still deeper observations with HST and the ACS camera.

The red GCs of NGC 1316 appear to have a power-law LF as well, though Goudfrooij et al. (2001b) at first found an exponent of $-1.23 \pm 0.26$. A reanalysis by these authors shows, however, that a calculational error was made and the true value is $-1.7 \pm 0.1$. Hence, in both NGC 1316 and NGC 3610 power-law LFs support the notion that the red GCs are of intermediate age.

A powerful tool for displaying evolutionary trends of GC systems as a function of age is the $\Delta(V-I)$ vs. $\Delta V_{10}$ diagram, which combines color and luminosity information (Whitmore et al. 1997). Figure 6 shows a version of this diagram in which $\Delta(V-I)$, the reddening-corrected color difference between the peaks due to second-generation GCs and to old metal-poor GCs, is plotted versus $\Delta V_{10}$, the magnitude difference between the 10th-brightest second-generation GC and the 10th-brightest old GC. Data points with error bars mark the locations of the GC systems for the galaxies of Fig. 4. Note that the seven GC systems lie roughly along the evolutionary track for second-generation model clusters of solar metallicity (solid line). This supports the notion that most second-generation GCs are relatively metal-rich ($[Z] \approx -0.8$ to $+0.2$), as verified spectroscopically for GCs in NGC 7252 (Schweizer & Seitzer 1998), NGC 1316 (Goudfrooij et al. 2001a), and M87 (Cohen, Blakeslee, & Ryzhov 1998). But above all, the $\Delta(V-I) - \Delta V_{10}$ diagram demonstrates quite clearly that the GC systems of the three merger galaxies and four ellipticals form an age sequence.

Along this sequence, NGC 1316, 3610, and 1700 seem to be good candidates for the kind of descendants of merged galaxy pairs that Ivan King was asking Toomre about at Yale (see §1). With new search techniques and astronomers’ growing interest in the subject, we can—during the next 5–10 years—expect
Figure 6. $\Delta(V-I) - \Delta V_{10}$ diagram showing color difference between 2nd-generation and old GCs plotted vs. magnitude difference between 10th-brightest 2nd-generation GC and its old counterpart. Points with error bars show values for GC systems of 3 merger galaxies and 4 Es. Lines give evolutionary tracks for model clusters of solar and 1/50th solar metallicity (Bruzual & Charlot 1996), and are marked with cluster ages in Gyr. Note that the observed seven GC systems form an age sequence. (After Whitmore et al. 1997, with some new data added.)

the discovery of many more transition objects in what I call the “King Gap.” Hopefully, some of these galaxies and their GC systems will fill in the presently still empty age range of about 0.5–3 Gyr. Realistically, however, we must face the fact that it will be difficult to find objects in the age range 1–2 Gyr, where intermediate-age metal-rich clusters blend in $V - I$ color with the old metal-poor clusters. In this age range, time-consuming spectroscopy will be required to separate the cluster subpopulations of different age and metallicity.

Nevertheless, the GC subsystems of intermediate age now known in about ten ellipticals do seem to form an evolutionary link between the young metal-rich GCs observed in recent merger remnants and the old metal-enriched GCs found in most giant ellipticals. This, then, seems to be a fitting present from us all to Ivan King on his 75th birthday!

5. Globular-Cluster Formation and Old Ellipticals

Given the observed propensity of globular clusters to form in the high-pressure environments of merger-induced starbursts (Schweizer 1987; Ashman & Zepf 1992; Jog & Solomon 1992; Elmegreen & Efremov 1997), GCs in old ellipticals (>7 Gyr) serve as valuable fossils of these galaxies’ early star-formation history. The discovery of bimodal GC populations in nearby ellipticals (Zepf & Ashman
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1993; Whitmore et al. 1995) has convinced many sceptics that major mergers played a role in forming at least the metal-rich, second-generation GCs, though alternative formation scenarios have been proposed as well. In a landmark study of M49 (= NGC 4472), Geisler et al. (1996) discovered that the metal-rich clusters lie on average closer to the center than the metal-poor ones, as predicted by Ashman & Zepf’s merger model. This solved the old puzzle of why some GC systems show steeper radial abundance gradients than their host ellipticals, a fact attributable in M49 to the radially varying ratio of metal-rich to metal-poor GCs. Mergers involve much gaseous dissipation, which explains quite naturally the stronger central concentration of second-generation clusters.

Kinematic differences between metal-poor and metal-rich globular clusters in E and S0 galaxies also seem to point to major mergers in the past history of these hosts. Both the outwardly increasing mean rotation of GCs in M87 (Kissler-Patig & Gebhardt 1998) and flips in the mean-rotation axis of the clusters as a function of radius (Côté et al. 2001) are difficult to explain in any monolithic-collapse model, but are a natural consequence of major mergers. In such mergers, old, pre-existing clusters from the halos of the input galaxies can be expected to acquire large velocity dispersions and significant outer rotation stemming from the galaxies’ orbital angular momentum. Second-generation clusters formed during the merger(s), on the other hand, should show lower velocity dispersions and less net rotation, as observed in M49 (Zepf et al. 2000).

Even in the radial distributions of GCs within their host galaxies we may begin to see an evolutionary sequence from young to old merger remnants. In young remnants (e.g., NGC 3921, 7252) the radial distribution of second-generation GCs is virtually identical to that of the galaxy light. This indicates that the young GCs and their progenitors experienced the same violent relaxation as did the average star, suggesting that the GC progenitors were relatively compact giant molecular clouds orbiting among the disk stars of the input spirals (Schweizer et al. 1996). There is tentative evidence for subsequent central erosion of GC systems, presumably due to tidal shocking of GCs during passages close to the center: At \( r = 1.2 \) kpc in NGC 1316, the radial distribution of GCs shows a deficit of \( \sim 45\% \) relative to the integrated star light (Goudfrooij et al. 2001b), while in old cluster ellipticals the corresponding deficit is significantly larger (e.g., Capuzzo-Dolcetta & Donnarumma 2001). Therefore, there appears to be a continuum of radial distributions of GCs ranging from young-cluster distributions as strongly centrally concentrated as the host merger remnants to old-cluster distributions typically less concentrated than the host ellipticals. It remains to be seen whether this tentative dynamical sequence will be confirmed as further examples of intermediate-age GC systems are added to the sample.

Perhaps the single most challenging question concerning GCs is why the old metal-poor GCs are so universally similar in all types of galaxies and environments. I believe that observations of cluster formation in present-day mergers and starburst galaxies have yielded a crucial clue: Whenever an ensemble of giant molecular clouds is exposed to a rapid pressure increase, a significant fraction of these clouds get shocked and turn into GCs (Jog & Solomon 1992). The question then is: Was there a universal pressure increase early in the history of the universe that might explain the surprisingly uniform ages and properties of old metal-poor GCs?
The cosmological reionization at $z \approx 7-15$ may have provided just such a universal pressure increase, which in turn led to the near-synchronous formation of metal-poor GCs from early giant molecular clouds (Cen 2001). If this hypothesis is correct, the following unified scenario of GC formation emerges.

Most globular clusters in the universe formed from shocked giant molecular clouds. The first-generation GCs formed near-simultaneously from pristine such clouds shocked by the strong pressure increase accompanying cosmological reionization. They populate all types of galaxies from dwarfs through spirals and ellipticals to giant cDs. Later-generation ("second-generation") GCs formed during subsequent mergers from metal-enriched giant molecular clouds present in the merging disks. Major mergers, some of which occur to the present time, led to elliptical remnants with a mixture of first- and second-generation GCs revealed by their bimodal color distributions. Minor mergers tended to form S0 galaxies and early-type spirals, again with a mixture of first- and second-generation GCs. However, unlike in ellipticals many of the second-generation metal-rich GCs in S0 galaxies may belong to a thick-disk population if they stem mainly from giant molecular clouds that belonged to the dominant input disk. Finally, a minority of "second-generation" GCs form sporadically from occasional pressure increases in calmer environments, such as in interacting irregulars or barred spirals.

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