THE EVOLUTION OF YOUNG STAR CLUSTERS IN MERGING GALAXIES

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1. Introduction

The formation of young star clusters in merging galaxies is, by now, well established. The new challenge is to use these young clusters as a tool to address some of the outstanding questions. For example, what fraction of these young clusters become globular clusters? Is this enough to explain the difference in the specific globular cluster frequencies for spirals and ellipticals? What is it about the collision between two gas-rich galaxies that triggers giant molecular clouds to form star clusters? Can the star clusters be used to age date merger remnants and establish a convincing evolutionary connection between merging spirals and elliptical galaxies? This review will focus on the last of these items.

2. A Brief History and Compilation of Recent Observations

A hint that young star clusters might be formed in mergers was provided by Schweizer's (1982) observations of six unresolved bluish knots in the merger remnant NGC 7252, which he suggested might be young star clusters formed during the merger. This idea was formally presented in Schweizer (1987) and Burstein (1987). Ashman and Zepf (1992) and Zepf and Ashman (1993) further developed these ideas, and made predictions about the bimodality of the metallicity histogram of the clusters. The most important pre- *HST* observation was made by Lutz (1991), who found a population of roughly a dozen blue, pointlike objects in the merger remnant NGC 3597, but was not able to resolve the objects.

The *HST* observations of NGC 1275 by Holtzman et al. (1992) was the primary catalyst in this active new field. They discovered a population of about 60 blue, pointlike objects and suggested that they were protoglobular clusters which formed $\leq$ 300 Myr years ago during a merger of NGC

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1275 with another galaxy. Unfortunately, NGC 1275, the central cooling-flow galaxy in the Perseus cluster, is such a peculiar galaxy that it is not clear which of its peculiarities is responsible for the formation of the young clusters (e.g., see Richer et al. 1993).

Whitmore et al. (1993), using *HST* observations (before refurbishment) of the prototypical merger remnant NGC 7252, found a population of about 40 blue, pointlike objects with luminosities and colors nearly identical to those found in NGC 1275. Unlike NGC 1275, with all its peculiarities, NGC 7252 is a fairly isolated galaxy which therefore provided a much cleaner connection between the formation of young star clusters and merging galaxies. Whitmore & Schweizer (1995) followed this up with pre-refurbishment observations of another prototypical merger, NGC 4038/4039 (= the "Antennae Galaxy", see Color plate 5, p. xxiii). Over 700 young star clusters were found in this galaxy.

Since then, every major merger observed by *HST* involving at least one gas rich galaxy has revealed the presence of young star clusters. In addition, *HST* has shown that non-interacting starburst galaxies and barred galaxies can also produce young star clusters, but in much smaller numbers than the major mergers. The lesson appears to be that luminous young star clusters are found whenever there is vigorous star formation. Since the ultraluminous *IRAS* sources are essentially all mergers (Sanders et al. 1988), it is not surprising that mergers show the largest populations of young star clusters. Observations of cooling flow galaxies by Holtzman et al. (1996) show that young star clusters are generally not found in these galaxies unless there is also evidence for a recent accretion event.

Covering the full range of related topics is not possible in a review of this length. Instead, Table 1 provides a list of articles (with a preference for recent results), and the reader is referred to Whitmore (1995; cooling flows), Schweizer (1996; mergers), and Ho (1996; starbursts) for related reviews. In the following sections we will focus on recent work concerning the evolution of star clusters in merging galaxies.

3. The Evolution of Young Star Clusters in Merging Galaxies

A typical old globular cluster, as found in our Milky Way galaxy, has an absolute magnitude in the V band in the range $-10 < M_V < -5$ mag, and a color in the range $0.8 < (V - I) < 1.1$ mag. The ages are estimated at ≈15 Gyr. Simple spectral evolution codes can be used to extrapolate these numbers backward in time to estimate the luminosities and colors of globular clusters at any epoch. The result is that the clusters, when they are, say, 5 Myr old, should be roughly 6 magnitudes brighter and 1.0 mag bluer in $V - I$ (based on the Bruzual & Charlot 1996 models). This is exactly what we find for the star clusters in merging galaxies.

Fig. 1 shows a set of simulations from Whitmore et al. (1997) demonstrating how the luminosities and colors of young- and intermediate-age globular clusters can be used to age date merger remnants. While it is easy to distinguish the young star clusters (solid circles) from the old population (open circles) for recent mergers, it becomes progressively more difficult with increasing age.

3.1. ONGOING MERGERS (< 100 MYR)

The "Antennae" galaxy (NGC 4038/4039) is the youngest and closest of the prototypical merger remnants on Toomre's (1977) list. While the extensive dust in NGC 4038/4039 widens the color distribution in Fig. 2 dramatically, it is obvious that there are hundreds of clusters in NGC 4038/4039 that are much brighter and much bluer than normal globular clusters, as predicted by Fig. 1.

Whitmore and Schweizer (1995) found that the cluster luminosity function is approximately a power law ($\phi(L)dL \propto L^{-1.78\pm0.05}dL$) with no hint of a turnover down to the limiting magnitude at $M_V = -10$ mag, unlike the luminosity function for old globular clusters which is a Gaussian. One possible explanation is that clusters of all masses are originally formed, but the fainter and more diffuse clusters are destroyed by a variety of processes (e.g., evaporation, tidal disruption, etc) resulting in a more Gaussian shaped distribution after a few Gyr.

Preliminary results from much deeper *HST* images taken with a repaired *HST* (Whitmore et al. 1998; Figure 1) show well over 1000 young clusters. These images are deep enough to detect the brightest stars so it will be possible to study many of the clusters on a star-by-star basis.

Another ongoing merger with a large population of very young clusters is NGC 6052, where Holtzman et al. (1996) estimate ages of ≈ 5 Myr for some of the youngest clusters. Many of these clusters do not appear to be as compact as Galactic globular clusters and they suggest that they may be massive associations. Others have compact cores which Holtzman et al. estimate to have masses of $\approx 10^6\ M_\odot$, and hence are good candidates for young globular clusters.

3.2. INTERMEDIATE-AGE MERGERS (0.1 GYR - 1 GYR)

Estimates of the ages of the galaxies NGC 3921 (Schweizer et al. 1996) and NGC 7252 (Miller et al. 1997) fall in the range 0.3 - 0.7 Gyr, based on post-refurbishment *HST* images. NGC 3597 is a similar merger remnant which Holtzman et al. (1996) estimate has an age less than 0.5 Gyr (most likely ≈ 200 Myr). In these galaxies the clusters are typically only 2 magnitudes

TABLE 1. Observations of Galaxies with Young Star Clusters

Reference	Brief Description
	(Mergers)
Schweizer (1982)	NGC 7252 (ground-based)
Lutz (1991)	NGC 3597 (ground-based)
Holtzman et al. (1992)	NGC 1275
Whitmore et al. (1993)	NGC 7252
Crabtree & Smecker-Hane (1994)	NGC 7727 (ground-based)
Whitmore & Schweizer (1995)	NGC 4038/4039
Borne et al. (1996)	the "Cartwheel" galaxy
Holtzman et al. (1996)	NGC 3597, NGC 6052
Schweizer et al. (1996)	NGC 3921
Hilker & Kissler-Patig (1996)	NGC 5018
Miller et al. (1997)	NGC 7252
Whitmore et al. (1997)	NGC 1700, NGC 3610, + compilation
Stiavelli et al. (1997)	NGC 454
Surace et al. (1997)	9 ultraluminous infrared galaxies
Zepf et al. (1997)	NGC 3256
Lee et al. (1997)	UGC 7636 (companion to NGC 4472)
	(Starbursts)
Arp & Sandage (1985)	NGC 1569
Kennicutt & Chu (1988)	LMC (30 Dor)
Meurer et al. (1992)	NGC 1705
Conti & Vaca (1994)	He 2-10
Hunter et al. (1994)	NGC 1140
O'Connell et al. (1994)	NGC 1569
Meurer et al. (1995)	9 starbursts
O'Connell et al. (1995)	M82
Watson et al. (1996)	NGC 253
Ho & Fillppenko (1997)	NGC 1705, NGC 1569 (spectra)
Calzetti et al.(1997)	NGC 5253
	(Miscellaneous)
Barth et al. (1995)	NGC 1097, NGC 6951 (barred)
Holtzman (1996)	Abell 496, 1795, 2029, 2597 (cooling flows)

brighter and 0.3 mag bluer in $V - I$ than old metal-poor globular clusters (see Fig. 2). The luminosity functions are still power laws down to the limiting magnitude with values of $\phi(L)dL \propto L^{-2.1\pm0.3}dL$ for NGC 3921 (151 cluster and association candidates), and $\phi(L)dL \propto L^{-1.8\pm0.1}dL$ for

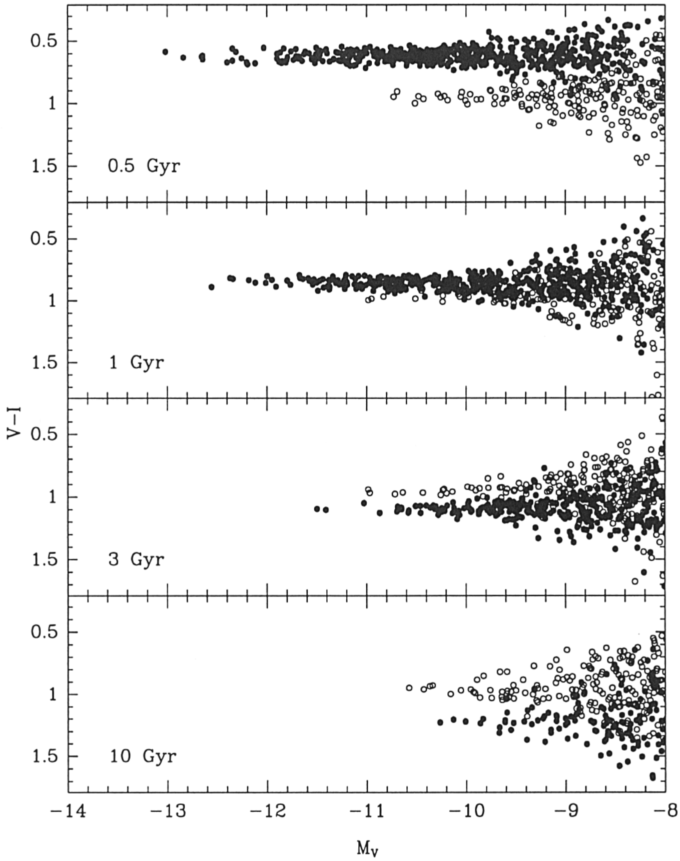

Figure 1. The evolution in the $V - I$ vs. V diagram of a young metal-rich population of globular clusters (filled circles) in the presence of a typical old metal-poor population of globular clusters (open circles). See Whitmore et al. (1997) for details.

NGC 7252 (499 cluster candidates).

van den Bergh (1995) has argued, based on the pre-refurbishment observations of the clusters in NGC 4038/4039 and NGC 7275, that the sizes of the young clusters are larger than typical values for old globular clusters (i.e., $R_{\rm eff} \approx 3$ pc). However, the more reliable measurements from post-refurbishment *HST* images yield upper limits of 5 pc for the median value in NGC 7252 (Miller et al. 1997), NGC 3921 (Schweizer et al. 1997), and NGC 3597 (Holtzman et al. 1996), hence this no longer appears to be a problem.

An important point is that by 0.5 Gyr the clusters are dozens of core crossing times old, hence they must be gravitationally bound and are not likely to disintegrate. Spectra of two of the brightest clusters in NGC 7252

(Schweizer & Seitzer 1993) and one cluster in NGC 1275 (Zepf et al. 1995) support this conclusion, showing strong Balmer absorption lines consistent with our age estimates of 0.5 Gyr. Finally, Ho and Filippenko (1996) have used high dispersion spectra from the Keck telescope to measure stellar velocity dispersions and determine masses of $3 \times 10^5\ M_\odot$ and $0.8 \times 10^5\ M_\odot$ for young clusters in NGC 1705 and NGC 1569. These masses are typical of normal globular clusters.

Similarities between the luminosity functions of young clusters, and the mass functions of giant molecular clouds (=GMCs), have lead several groups to suggest that the progenitors of the young star clusters found in mergers are GMCs, and to propose various models for their formation (e.g., Jog and Solomon 1992, Harris & Pudritz 1994, Schweizer et al. 1996, Elmergreen & Efremov 1997).

Estimates of the specific frequencies of globular clusters after 15 Gyr are 2.9 for NGC 3921 (Schweizer et al. 1996) and 2.5 for NGC 7252 (Miller et al. 1997). Hence it appears that these two galaxies will have specific frequencies typical of field ellipticals.

3.3. OLD MERGERS (1 - 5 GYR)

If young star clusters in merger remnants have roughly solar metallicity (see Whitmore et al. 1997) then Bruzual-Charlot (1996) models predict that 1 Gyr old clusters should have roughly the same colors as old globular clusters. However, they will still be 1 - 2 magnitudes brighter than old globulars. As the clusters continue to age the signatures will become even more subtle, with clusters predicted to be essentially identical in brightness and only $\Delta\ (V - I) \approx 0.2$ mag *redder* (due to higher metallicity) at an age of 5 Gyr.

Evidence for a population of star clusters with ages of 4 ± 2.5 Gyr has been found in NGC 3610, a galaxy with a high "fine structure" index (e.g., loops, shells, etc.) indicative of past merging activity (Schweizer & Seitzer 1992). A population of luminous red clusters which are ≈ 0.7 mag brighter and ≈ 0.2 mag redder in $V - I$ are reported in Whitmore et al. (1997). In addition, most of these red clusters are found near the center of NGC 3610 (see Figures 4 and 11 from Whitmore 1997), as predicted for clusters formed in mergers by Ashman & Zepf (1992) .

3.4. NORMAL ELLIPTICALS (> 5 GYR)

As shown in Fig. 1, and first discussed in Zepf & Ashman (1993), if elliptical galaxies are the products of mergers between spiral galaxies, and new metal-rich globular clusters are produced during these merger, we should expect bimodal color distributions for the globular clusters after a few Gyr.

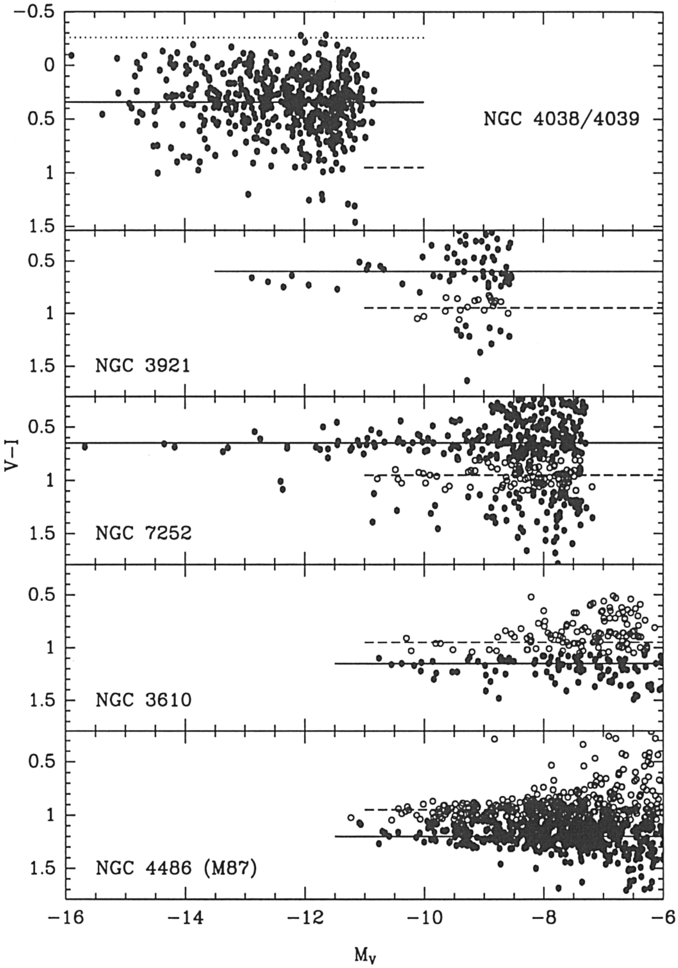

Figure 2. The $V - I$ vs. M_V diagram for five galaxies observed by *HST* suspected of being merger remnants. Compare these observations with the simulations shown in Fig. 1. See Whitmore et al. (1997) for details.

Evidence that the majority of old ellipticals do in fact have bimodal color distributions has accumulated over the past several years (see Zepf article in this volume), with perhaps the best example being M87 (Whitmore et al. 1995, Elson & Santiago 1996, Kundu et al. 1998), with a population of blue ($V - I = 0.95$ mag) metal-poor clusters believed to be the original population of clusters, and a population of red ($V - I = 1.2$ mag) clusters probably formed by gas rich mergers.

Fig. 3 shows in more detail than Fig. 1 how the luminosities and colors of the clusters can be used to follow the evolution of star clusters in merger

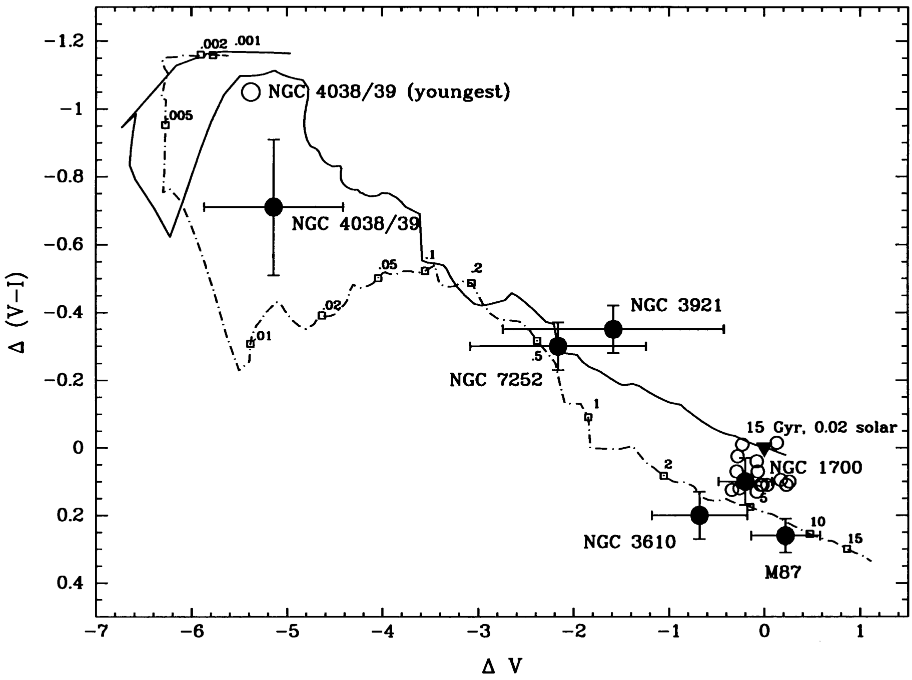

Figure 3. The $\Delta(V-I)$ vs. ΔV diagram for the six galaxies from Whitmore et al. (1997), superposed on Bruzual-Charlot (1996) tracks for a metal-poor population (solid line) and a solar metallicity population (dashed-dot line). The values are normalized to an old, metal-poor population (filled triangle). Typical elliptical galaxies are included as small circles. Ages in Gyr for the solar metallicity track are marked with squares.

remnants. The lines show the predictions from Bruzual-Charlot models for a metal-poor population (solid) and a solar metallicity population (dot-dashed). See Whitmore et al. (1997) for details.

Although the observed colors in M87 fit the model quite nicely, Forbes, Brodie, & Grillmair (1997) point out a problem with the relative numbers of red-to-blue clusters in M87. The specific frequency in M87 is extremely high, which would require several times more red clusters than blue clusters if the increase is due to the addition of metal-rich clusters formed during a gas-rich merger. This is an important result, and probably indicates that cD galaxies like M87 have had a more complicated formation history than the simple spiral + spiral = elliptical scenario. It is likely that M87 has accreted a large number of dwarf galaxies as well as the outer portions of galaxies throughout the galaxy cluster. Both would be rich in blue, metal-poor clusters. Furthermore, the initial formation of the seed galaxy that was to become M87 probably occurred very early, and may have involved galaxies with lower metallicity (i.e., high gas-fractions) hence forming metal-poor, blue globular clusters.

4. Summary

The fact that mergers between gas-rich galaxies can produce large numbers of young, very luminous, compact star clusters is now well established. The brightest of these star cluster have the right luminosities, colors, spectra, sizes, and distributions to be young globular clusters. Attempts to use the colors and luminosities to trace out an evolutionary sequence of merging galaxies are showing promising results (Fig. 3), although the numbers in the sample are still small.

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