Massive Stellar Clusters in Interacting Galaxies

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Abstract. Massive clusters are now seen to form easily in interacting and merging galaxies, making these excellent environments for studying the properties of young clusters. New observations of the Antennae (NGC 4038/39) show that the most luminous young clusters do not have a measurable tidal radius. Most observations suggest that the luminosity function (LF) and mass functions of young clusters are single power laws. However, there are many uncertainties at the faint end of the LF. For example, contamination from massive stars may be important. The shape and evolution of the LF, and more fundamentally, the mass function, of massive clusters had implications for our understanding of both the formation and the destruction of massive stellar clusters.

1. Introduction

Ten years ago there were only suggestions that interacting and merging galaxies contained young, massive star clusters (Schweizer 1982; Lutz 1991). However, subsequent observations, especially those using the Hubble Space Telescope, have shown that young clusters are nearly ubiquitous in such systems. Table 1 of Schweizer (1999) gives a nearly complete list of galaxies observed to have young star clusters. To this list can be added recent papers on NGC 3597 (Carlson et al. 1999; Forbes & Hau 1999) and NGC 5128 (Holland et al. 1999). It would seem that cluster formation is a natural result of the star formation triggered by strong gravitational interactions or direct collisions.

Many of these observations were motivated by the question of whether ellipticals can form from the mergers of two spirals, but, in addition, they provide important information about the formation and evolution of the star clusters themselves. The sizes and profiles of the youngest clusters can constrain their initial states. The distribution of ages gives the cluster formation history, which can be compared with the dynamical and star formation histories. The ages and metallicities allow us to determine masses and the mass function. This is critical for understanding the physics of how clusters form. The evolution of the mass function then shows us how the interplay between stellar evolution and both internal and external dynamics affect cluster evolution. This paper will review the sizes, ages, and masses of young star clusters in merging galaxies. The focus will be on recent results from WFPC2 observations of NGC 4038/39 (“the Antennae”, Whitmore et al. 1999, hereafter W+99; Zhang & Fall 1999, hereafter ZF99) and NGC 7252 (Miller et al. 1997, hereafter M+97).
2. Cluster Sizes

The sizes of the star cluster candidates determine whether they are structurally similar to Galactic globular clusters (GCs) with effective radii of a few parsecs, or to open clusters and associations which can have a much wider range of sizes but which are generally bigger than GCs. The sizes and profiles of the youngest clusters are also important initial conditions for dynamical models of clusters (see Zwart’s comments in the Discussion). In addition, Galactic GCs have a lognormal or broken power-law mass function with a characteristic mass of about $10^5 M_\odot$, while open clusters have an unbroken power-law mass function. Thus, density could be related to formation process. Pre-refurbishment HST images of NGC 4038/39 and NGC 7252 showed the cluster candidates to have $R_{\text{eff}} \gtrsim 10$ pc and a power-law luminosity function. Thus, it was argued that these objects would not become GCs and that galaxy mergers would not produce GC systems like seen in elliptical, calling into question whether ellipticals were produced by mergers (van den Bergh 1995)

Observations with the corrected optics of WFPC2 have consistently shown that the bulk of the young cluster candidates are marginally resolved and that $R_{\text{eff}} \lesssim 5$ pc (Schweizer et al. 1996; Whitmore et al. 1997; M+97; Carlson et al. 1999; W+99). Thus, the effective radii are consistent with the values for old GCs in M87 (Whitmore et al. 1995) and the Milky Way. As suspected, the larger effective radii measured previously were due the difficulty of measuring sizes on the aberrated WF/PC1 images.

In the Antennae we may now be seen changes in both the effective and tidal radii with age (see Section 3). Old cluster candidates have $\langle R_{\text{eff}} \rangle = 3.0 \pm 0.3$ pc while young and intermediate age cluster candidates have $\langle R_{\text{eff}} \rangle = 4.6 \pm 0.4$ pc. Further, the tidal radii of the young clusters can be much larger than for the old clusters (Figure 1). Thus, the density distribution of clusters may extend beyond their tidal radii at birth and a few orbits around the galaxy are needed to remove the stars beyond the tidal radius.

3. Metallicities and Ages

Since broad-band colors are degenerate in age and metallicity, we must have an independent measurement of one of these properties in order to determine the other from evolutionary models. Spectroscopy of the brightest three young clusters in NGC 7252 shows that they have near-solar metallicity (Schweizer & Seitzer 1998), so solar metallicity is assumed for all the young clusters. Then, ages are determined by comparing the broad-band colors and luminosities with evolutionary models for simple stellar populations. The youngest clusters are often surrounded by considerable dust, so we attempt to correct for this internal extinction by calculating “reddening-free” indices based on the $(U-B)$, $(B-V)$, and $(V-I)$ colors (M+97; W+99). In NGC 4038/39, the youngest clusters are also be distinguished by their Hα emission.

Multiple populations of star clusters can be distinguished in several systems. Four populations have been identified in the Antennae: 1) a $< 10$ Myr-old population with compact Hα emission located near the dusty overlap region; 2) a $\sim 100$ Myr-old population found further out in the disk of NGC 4038; 3) a
Figure 1. Radial surface brightness profiles of three star clusters in NGC 4038/39: the very extended and luminous Knot S, its neighbor #430 (both with ages < 10 Myr), and the 500 Myr-old cluster #225. Neither of the youngest clusters have a measurable tidal limit, unlike the older cluster which has a tidal radius of about 50 parsecs (W+99).

∼ 500 Myr-old population that may have been formed during the first close encounter when the tidal tails were formed; and 4) a few ∼ 10 Gyr-old clusters that are probably original GCs from the progenitor galaxies (W+99). The very young ages of the youngest clusters are confirmed by ultraviolet spectroscopy (W+99) and infrared spectroscopy (see the contributions by Gilbert and Mengel). The older merger remnant NGC 7252 has a < 10 Myr-old population of rather extended clusters associated with the central gas disk, a 500–800 Myr population that formed during the merger, and old clusters from the progenitor galaxies (M+97). Young cluster formation lasts for several hundred Myr, consistent with the dynamical time-scale of the merger event.

4. Luminosity and Mass Functions

WFPC2 observations of young star clusters have most often found the luminosity functions (LFs) to have a power-law shape, $\phi(L) \propto L^\alpha$, with $\alpha \approx -1.8$ down to the completeness limits of the observations (e.g. Schweizer et al. 1996; M+97; Carlson et al. 1999). The masses of the most luminous clusters, as inferred from evolutionary models of the appropriate age and metallicity, can approach $10^8 M_\odot$, over an order of magnitude more massive than the most massive Galactic GC (Schweizer & Seitzer 1998). These are extreme clusters, even considering the fact that the mass-to-light ratios of the models are about a factor of two higher than measured (Fritze-v. Alvensleben, this proceedings). At the faint end, the new observations are sensitive enough detect objects less massive than
Figure 2. Reddening and completeness-corrected LF of young star clusters in NGC 4038/39. The cluster candidates are taken from regions on the PC which are dominated by clusters rather than stars (W +99). The LF has a bend at a luminosity corresponding to $\sim 10^5 M_\odot$.

$10^5 M_\odot$, the mass at the peak of the old GC mass function. If the mass function were peaked, then one would expect to see a bump in the luminosity function since fading preserves the shape of the luminosity function. This immediately suggests that the mass function is a power law. However, one must be sure that large relative age spreads, reddening, and stellar contamination do not affect the shape of the cluster luminosity function (cf. Meurer 1995).

A few observations are now suggesting that the young cluster LF may not be a single power law. Zepf et al. (1999) find that the LF for young clusters in NGC 3256 to be slightly flattened for $M_B > -11$. However, the statistical significance of the flattening is relatively weak (2.5$\sigma$) and the most likely mass function is a power law with $\alpha = -1.8$. The new observations of the Antennae show a stronger flattening of the luminosity function (Figure 2). The break occurs at a mass of $\sim 10^5 M_\odot$, similar to the peak in the old GC mass function. While this is suggestive that the mass function has a break or peak, a reconstruction of the mass function by ZF99 shows that it is still most likely a single power law with $\phi(M) \propto M^{-2}$.

The proximity of the Antennae, the depth of the photometry, and the youth of the starburst made stellar contamination a significant issue. However, stellar contamination at the faint end of the cluster LF may be significant even for the older and more distant merger remnants like NGC 3921 and NGC 7252.

I have attempted to determine the young cluster mass function in NGC 7252 by matching the observed LF with Monte Carlo simulations. Artificial clusters are drawn from either a power-law mass function consistent with the GC mass function of the Galaxy, or a power-law mass function with slope equal to the observed slope of the cluster LF. The masses are converted to magnitudes and colors using Bruzual & Charlot (1996) evolutionary models of simple stellar populations. Young clusters are assumed to have solar metallicity, and the mean age is determined by matching the $(V-I)$ colors of the clusters. Some simulations also include artificial stars drawn from a Salpeter IMF and placed in the color-magnitude diagram using Geneva evolutionary tracks (Schaller et al. 1992) and bolometric corrections from Bessell, Castelli, & Plez (1998) for solar metallicity.
Figure 3. Luminosity functions for observed and simulated star clusters in NGC 7252. The mean age of the simulated clusters is \( \tau = 650 \text{ Myr} \) and the curves are for different age spreads, \( \Delta \tau \) [Myr], which do not have a significant effect. a) The mass function is lognormal. These models are not good matches to the data. b) The mass function is a power-law with \( \alpha = -1.8 \). Values of \( \chi^2/\nu \approx 1 \) indicate that the simulations are good representations of the observations.

Measurement error and selection criteria are applied to the simulations before comparing them with the observations. Gaussian-distributed random errors are added to the colors and magnitudes of model clusters and stars based on the photometric uncertainties of the observed clusters. Then, both the observed and simulated clusters are selected according to the same criteria. The goodness-of-fit between a simulation and the observations is measured by the \( \chi^2 \) per degree of freedom, \( \chi^2/\nu \).

If all the observed objects are clusters, then the mass function is a power law with slope \( \alpha \approx -1.8 \) (Figure 3). However, stellar contamination at the faint end of the cluster LF may be important. Using a star formation rate (SFR) measured from H\( \alpha \) images results in more objects at faint magnitudes than are observed. With young cluster drawn from a lognormal mass function, the SFR needed to match the observed LF is about half the observed SFR (Figure 4). This difference could be explained if the binary fraction is about 50%. The observed SFR could be much lower if the H\( \alpha \) flux is due to shocks or other processes besides star formation. Most of the flux in the region under consideration is from diffuse emission rather than discreet HII regions. The mass-loss prescription in the stellar evolutionary tracks is also a crucial parameter; higher mass-loss rates yield fewer supergiants. The main point is that determining cluster mass functions is complicated, all these factors must be considered.

5. Conclusions

The study of young star clusters in interacting and merging galaxies is a good example of the symbiotic relationship between observations and theory. Observations of the youngest star clusters in the Antennae are providing the initial
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Figure 4. As Figure 3, except that the mass function of the simulated clusters is lognormal and the steeply rising faint end of the LF is populated by supergiant stars formed with SFR = 0.15 \( M_{\odot} \) \( yr^{-1} \). The statistical match to the data is similar to the power-law models in Figure 3b.

...density distributions and the initial cluster mass function that are needed for models of individual star clusters and cluster systems. Further observations of older merger remnants will hopefully show how the mass function evolves with time. On the other hand, evolutionary models are needed to convert colors and luminosities into ages and masses. Dynamical models will explain the processes that cause clusters and cluster systems to evolve.

The current observations suggest that young clusters may be born without a tidal radius, that cluster formation occurs over several hundred Myr in a merger, and that the mass function of young clusters is most likely a power-law (though there are indications of flattening). Thus, there still appears to be a difference between the mass functions of young clusters and old GCs. This could be due either to the effect of different initial conditions at recent epochs (e.g. increased metallicity) or to the slow destruction of low-mass clusters over a Hubble time (see ZF99 and references therein).

Acknowledgments. I would like to thank the Leids Kerkhoven Bosscha Fonds for a subsidy that allowed me to attend this workshop. Rob Kennicutt and Audra Baleisis kindly provided the H\( \alpha \) image of NGC 7252. Thanks to Michael Fall, Brad Whitmore, and Gerhardt Meurer for many useful suggestions on modeling the cluster mass function.

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Discussion

C. Boily: How is the tidal radii of candidate clusters estimated? What might be the velocity dispersion of populations of candidate clusters?
B. Miller: The tidal radius depends on the shape of the potential, which is complicated in a merging system. However, the potential of a young merger like NGC 4038 may still not be too different from a normal disk. Thus, we can get a range of likely tidal radii by looking at the Galaxy, M31, and truncated clusters in the Antennae itself. They do seem to be similar, with values of $r_t = 50 - 100$ pc. The velocity dispersion of the cluster system is probably on the order of 100 km sec$^{-1}$ (see Schweizer & Seitzer 1998).
S. P. Zwart: The luminosity density of your youngest globular cluster seems to extend beyond its tidal radius in the potential of its parent galaxy. The small age of this system may be smaller than the cluster’s crossing time, which suggests that when clusters form their density distribution extends beyond the tidal radius. This is important for understanding the initial conditions of globular clusters, which are required for numerical models.
P. Kroupa: The flattening of the LF near $10^5 M_\odot$ may be due to cluster-cluster disruptions in cluster-rich regions. Are there any HST images for tidal dwarf galaxies?
B. Miller: HST images of tidal dwarf candidates in NGC 4038/39 and NGC 7252 have been taken and are being analyzed.
J. C. Mermilliod: The important point is to distinguish a real bound star cluster from a large OB association which can cover several hundred parsecs. Galactic examples would be the Sco OB1 region with a dense cluster and a whole population of supergiants, or the h and χ Persei region.
B. Miller: Agreed, we try to select as cluster candidates only the most compact objects that do not appear to be stars.