Large numbers of young stars are formed in merging galaxies, such as the Antennae galaxies. Most of these stars are formed in compact star clusters (i.e., super star clusters), which have been the focus of a large number of studies. However, an increasing number of projects are beginning to focus on the individual stars as well. In this contribution, we examine a few results relevant to the triggering of star and star cluster formation; ask what fraction of stars form in the field rather than in clusters; and begin to explore the demographics of both the massive stars and star clusters in the Antennae.

1. Introduction

It is now well accepted that most star formation occurs in clustered environments, such as associations, groups and clusters (e.g., Lada & Lada 2003). In addition, it is clear that star formation is greatly enhanced in merging galaxies, making them an excellent place to study the formation of large numbers of young, massive stars, albeit with the disadvantage of having to work with stars at larger distances than the nearby groups and clusters in our own galaxy. In keeping with their galactic counterparts, most of the stars in merging galaxies also form in clusters, the brightest and most compact of which have been dubbed “super star clusters.” Hence, understanding what triggers the formation of star clusters in mergers may be an important clue for understanding the formation of stars in general.

The excellent spatial resolution of the Hubble Space Telescope (HST) has rejuvenated the study of young star clusters in recent years (e.g., see reviews by Whitmore 2003, and Larsen 2005). One of the most important results is that the brightest of the super star clusters have all the attributes expected of young globular clusters (e.g., Holtzman 1992). An equally important result is that most of the groups and clusters do not appear to be bound, with roughly 90% being dispersed into the field each decade of log time (i.e., “infant mortality”; Whitmore 2003; Fall 2004; Fall, Chandar, & Whitmore 2005). Hence, understanding the destruction of clusters may be the key to understanding the demographics of both star clusters and field stars.

The Antennae galaxies (NGC 4038/39) are the nearest and youngest prototypical merger in the Toomre (1977) sequence. Hence, they may be our best chance for studying the formation of super star clusters and the massive stars within a major merger. While other galaxies will be briefly discussed at various parts of this review, the Antennae will be our centerpiece. Figure 1 shows an example of some of the super star clusters in the Antennae (two left panels). Knot S, shown in the upper left, will be the focus of several parts of this paper. The central cluster in Knot S contains at least $10^7 M_\odot$ alone, while the entire region contains well over $10^8 M_\odot$. Note that Knot S consists of more than a single cluster. While it is difficult to distinguish individual supergiant stars in the outer region from faint clusters based on this image alone (this will be the main subject of §4), at least a dozen objects are clearly resolved, and hence are sizeable clusters in their own right. To provide some perspective, Figure 2 shows a superposition of what 30 Doradus ($M_V \approx -10, \approx 10^5 M_\odot$) would look like at the distance of the Antennae.

While a great deal of attention has been paid to the study of super star clusters in
external galaxies during the past decade, relatively little work has been done on the demographics of individual stars in these galaxies. Reasons include the larger distance, which makes it difficult to study anything but the brightest stars, and the high degree of crowding due to the large number of stars and the clustered nature of star formation. In general, it would seem that a detailed study of nearby star formation regions, such as the Orion Nebula, would be more fruitful. However, there are two basic reasons why it is important to study individual stars in more distant galaxies as well. The first is the opportunity to study larger samples of stars (e.g., $\approx 10^7$ in Knot S) in a specific cluster. This would allow us to determine whether the most massive star in a cluster is determined by statistics or physics (see Weidner & Kroupa 2006; Elmegreen 2005; and Figer 2005 for discussions). Another motivating factor is to determine whether there are two modes of star formation (i.e., violent and quiescent; Gallagher 2004) which result in different stellar IMFs.

In this contribution we will first examine what has been learned about the triggering of star and star cluster formation in the Antennae. We will then address the question of whether essentially all stars form in clustered environments. We will also explore whether there is any evidence for an upper mass cutoff for the stellar IMF in the Antennae. Finally, we will describe an effort to develop a general framework for understanding the demographics of both stars and star clusters.
2. What triggers the formation of star clusters (and hence stars) in the Antennae?

It is clear that shocks play an important role in triggering star formation. However, what is not clear is how they do this. One popular mechanism for triggering star formation in merging galaxies has been high-velocity cloud-cloud collisions (e.g., Kumai, Hashi, & Fujimoto 1993 suggest that collisions with relative velocities in the range 50–100 km s$^{-1}$ are required).

Whitmore et al. 2005 obtained long-slit spectroscopy using STIS on HST to address this question. They found that the velocity fields are remarkably quiescent, with RMS dispersions less than about 10 km s$^{-1}$, essentially the same as in the disks of normal spiral galaxies (Figure 3). This does not support models that rely on high-velocity cloud-cloud collisions as the triggering mechanism, but is consistent with models where a high pressure interstellar medium implodes the GMCs without greatly affecting their initial velocity distribution (e.g., Jog & Solomon 1992). This also supports earlier results (Zhang, Fall, & Whitmore 2001) that found essentially no correlation between star cluster formation and the velocity gradients and dispersions of H$_\alpha$, H$_\text{i}$, or CO. In retrospect, this is also evident from the existence of a large number of young clusters in the disk-like regions of NGC 4038, which still has a relatively quiescent, disk-like rotation curve (see Amram et al. 1992).

Another approach is to look for evidence of triggering by age-dating clusters and looking for a pattern of older star formation (the initial burst) surrounded by younger star formation (more recent bursts). Evidence for this has been seen around 30 Doradus (e.g., Walborn et al. 1999), with the youngest star formation at the tips of “pillars” pointing back towards the central object.
Figure 3. Hα velocities based on long-slit observations using the STIS detector on HST. Note how small the velocity dispersion is for a given subregion (e.g., $\approx 10$ km s$^{-1}$ for region F, once the large scale gradient is removed). See Whitmore et al. 2005 for details.

Perhaps the central question here is not whether star formation can be triggered by previous star formation, which it clearly can, but how important this effect is (Whitmore 2003). Put another way, is local triggering more important, or global triggering? Few attempts have been made to try to quantify this. Figure 4 shows some evidence for sequential triggering around Knot S of the Antennae, with a clump of older clusters near the center (>10 Myr, circles), intermediate-age clusters further out (3–10 Myr, crosses), and a few very young clusters still further out (<3 Myr, squares). We note that the clear clumping of the different ages shows that we are able to measure ages reasonably well, at least on a relative scale. If there was a very large amount of scatter in determining the ages we would find the different ages more randomly arranged in Figure 4.

In general, the fraction of luminosity in succeeding generations of star clusters appears to continuously decrease (i.e., each new generation does not produce a comparable generation, so that the process cannot continue in equilibrium). Hence, we conclude that triggered star formation is a significant, but not dominant, component of the overall star formation in the Antennae. More global processes, such as interactions and spiral arms, appear to be the primary drivers.
3. What fraction of stars are formed in clusters?

It is well recognized that for the Milky Way, most stars are formed in associations, groups and clusters (e.g., Lada & Lada 2003). De Wit et al. (2005) provide a recent demonstration of this. They use proper motions from Hipparcos to estimate that only $4\pm2\%$ of the O and B stars in the Milky Way formed outside of groups or clusters (i.e., most of the O and B stars in the field are consistent with being runaway stars from nearby groups.)

What have we learned on this subject from external galaxies, and in particular from the Antennae? Several early studies of star clusters in merger and starburst galaxies found that 10–50% of the UV light (i.e., young stars) are found in clusters (e.g., Meurer 1995; Zepf et al. 1999; Whitmore & Zhang 2002). The initial fraction of stars in clusters is even higher than these estimates, since at least some clusters don’t survive. In fact, as we shall see in §5 (also see Fall, Chandar & Whitmore 2005), we believe that roughly 80–90% of clusters disperse or are destroyed each decade of log time. Furthermore, our model, which incorporates this effect, predicts that if all stars are formed in clusters, the amount of UV light we should observe in clusters should be $\approx8\%$ for the Antennae, in good agreement with observations ($\approx9\%$; Whitmore & Zhang 2002). See Fall, Chandar, & Whitmore (2005) for a related calculation using total Hα flux, again concluding that the observations are consistent with the idea that essentially all stars are formed in groups or clusters.

A related question is: What are the relative fractions of stars formed in associations,
open clusters, and super star clusters? This is a difficult question to answer for a variety of reasons. First, there is no clear dividing line between these types of groupings, (i.e., they probably represent a continuum rather than distinct modes). Second, the objects are barely resolved, and are often found in very crowded regions, making it difficult to reliably separate the objects into more than a single bin. In addition, it is not clear how diffuse an open cluster or association needs to be before it falls out of the sample because it cannot be detected. It is interesting to note, however, that we seem to be able to account for essentially all of the UV light in the Antennae by stars that originally formed in groups and clusters (either still existing within clusters we detect, or from stars where the cluster has already dispersed). This suggests that a large fraction of stars are not formed in very diffuse associations that would be too faint to be in our sample.

We should also keep in mind that even clusters that survive will lose a large fraction of their stars from their outer halos. For example, Whitmore et al. 1999 found that young clusters like Knot S have linear profiles, while older clusters have tidally truncated profiles, implying the removal of a large fraction of light from the outer regions (see Schweizer 2004 for a review on the sizes and radial profiles of clusters). In fact, we estimate that ≈50% of the light in Knot S falls beyond 50 pc from the center, a typical tidal radius for a globular cluster.

Bastian & Goodwin (2005) find similar profiles for the young clusters in M82, N1569, and N1705. They suggest that these profiles are compatible with N-body simulations of clusters with rapid removal of mass due to gas expulsion, hence supporting the basic interpretation that a large fraction of stars from clusters will eventually find themselves in the field. Fall, Chandar, & Whitmore (2005) make a similar argument to explain the high infant mortality rate of clusters in the Antennae.

Comparisons between UV spectra from clusters, and from the diffuse field stars between clusters, provides another line of reasoning that supports this basic picture. For example, Chandar et al. (2005) find that the integrated spectrum of the field stars in several local starburst galaxies is consistent with formation of the stars within clusters which dissolve with typical time scales of 7–10 Myr.

4. What can we learn about the stellar content of the super star clusters in the Antennae?

In Whitmore et al. (1999), one of our primary difficulties was differentiating stars from clusters. This led us to conclude that the number of young star clusters in the Antennae was between 800 and 8000—a pretty big range! Our new ACS data, with its better spatial resolution, provides a better opportunity for making this determination and for studying the stars in their own right.

An important tool we are employing in this analysis is a maximum-likelihood SED-fitting software package named CHORIZOS, which is described in Maíz-Apellániz (2004). Ubeda, Maíz-Apellániz, & MacKenty (2006) employed CHORIZOS to analyze HST observations in six filter bands (F170, F336W, F555W, F814W, J, H) of NGC 4214, a nearby (3 Mpc) starburst dwarf galaxy. Their main conclusions are: 1) extinction is quite patchy, but relatively low around all but the youngest clusters, 2) 10 of the 12 clusters they studied have ages <10 Myr (note that this supports the infant mortality discussion that will be described in §1 and §5), 3) the blue-to-red supergiant ratios are consistent with theory, 4) the stellar IMF in the field is steeper than −2.8. This study is a good example of how researchers are starting to study both the stellar and cluster contents of external galaxies. In the current paper, we use CHORIZOS to estimate values of $M_{\text{bol}}$ and $T_e$ for candidate stars in the Antennae.
We first ask the question: How well can we distinguish clusters from stars in Knot S of the Antennae galaxies, based only on a concentration index (i.e., the luminosity of an object inside a 3 pixel radius compared to the luminosity inside a 1 pixel radius)? Figure 5 shows four luminosity ranges drawn from the sample of point-like objects around Knot S,
starting with the brightest objects ($M_V < -10$; bottom left), and ranging to the fainter objects ($-7 < M_V < -8$; in the upper right). The objects with profiles indistinguishable from stars are shown as open squares, while the resolved objects are solid circles. The data is plotted on a $U - B$ vs. $V - I$ color-color diagram with Bruzual & Charlot (2003) solar metallicity models superposed on all four panels using solid lines (young clusters are in the upper left and old clusters in the lower right; locations for 1- and 8-Myr clusters are shown on the bottom left figure). Padova models of stars brighter than $M_V = -7$ are shown by the dashed lines in the bottom left panel. The dotted line shows the reddening vector, and also acts as a rough dividing line between “cluster-space” (upper right) and “star-space” (lower left). This works because essentially all of the objects in this region are young, hence there are no clusters that populate the bottom part of the Bruzual & Charlot cluster models.

Several conclusions can be drawn from this figure. The first is that if we select only the brightest objects (i.e., $M_V < -10$), they are all consistent with being young clusters ($<8$ Myr) with relatively little extinction (i.e., they are very close to the Bruzual-Charlot models). This is reassuring, since the brightest stars might be expected to be fainter than $M_V \approx -9$ (i.e., the brightest stars in the Milky Way; Humphreys 1983). This is the value we—and several other researchers—have used to conservatively identify clusters in the past (e.g., Whitmore et al. 1999).

If we cut the sample at $M_V < -9$ (lower right panel), things get a little more interesting. Near the bottom of the diagram we now have three point-like objects in Knot S in the part of the diagram appropriate for stars. These all happen to have values of $M_V \approx -9.1$, just slightly brighter than our boundary condition between stars and clusters. We also find three point-like objects in or near cluster-space. This is our second important result, that while the concentration index is useful for telling the difference between clusters and stars, it is only partially successful. It appears that some clusters (based on their position in color-color space) are so concentrated that they cannot be distinguished from stars based on their size alone. This is also apparent from the fainter bins (upper panels), where a majority of the point-like objects are found in star-space, but a fair fraction are also found in cluster-space.

Another interesting point is that while most of the resolved objects in the $-10 < M_V < -9$ diagram hug the Bruzual-Charlot models very nicely, about a half-dozen objects are just below the dotted line used to separate cluster- and star-space. We believe most of these are cases where there is a mixture of light from both a cluster and from one or two bright stars in the cluster (i.e., if you added the light from a cluster sitting on the Bruzual-Charlot cluster track and one of the three stars at the bottom of the diagram, which have roughly the same brightness, the result would be an object with an intermediate color). This does not happen for the brightest clusters (i.e., with $M_V < -10$) because these clusters have enough stars that one or two random bright stars cannot greatly affect the total color. Hence, a certain degree of “stochasticity” appears for young clusters with magnitudes around $M_V \approx -9$ (i.e., masses around $10^4 M_\odot$). This effect has already been noted by other authors such as Cervino, Valls-Gabaud, & Mass-Hesse (2002). Ubeda, Maíz-Apellániz, & MacKenty (2006) also show a nice example of a cluster that appears to have both a blue and a red supergiant superposed.

Our fourth, and perhaps most important result, is that roughly 50% of the objects fainter than $M_V < -9$ are clusters, based on their position in the color-color diagram. This is actually a very conservative lower limit, since, as we just noted, some of the objects around the dividing line are likely to be clusters with one or two stars pulling them just below the dividing line. This has a number of important ramifications, the most important being that it shows that the number of faint clusters continues to rise
Hence, neither the concentration index (i.e., size), nor the position in the color-color diagram alone is completely successful in separating stars and clusters. What if we use a combination of both criteria? Figure 6 ($M_{\text{bol}}$ vs. $\log T_e$ diagrams for candidate massive stars around Knot S) shows that this appears to work fairly well. Using either the size or color criteria alone implies the existence of stars that are more massive than the stellar tracks (two upper panels in Figure 6). However, if we use both criteria simultaneously, all the remaining objects are consistent with being normal stars. We might note that this also suggests that there is an upper limit to the maximum mass of a star, since we would

![Figure 6](image_url)

**Figure 6.** $M_{\text{bol}}$ vs. $\log T_e$ for candidate stars in Knot S, using only a size selection, only a color selection, or both a size and color selection. Note that using a combination of the size and color criteria does a good job of removing the clusters from the stars (i.e., the remaining objects are in the part of the diagram expected for stars). See text for details.

in a power law fashion. This provides a counter example to the claims that the initial cluster mass function in some galaxies may be a Gaussian (e.g., de Grijs, Parmentier, & Lamers 2005), since a Gaussian would require that essentially all the faint objects were individual stars. Another ramification is that the quantity of clusters in the Antennae numbers in the thousands, rather than the hundreds.

Hence, neither the concentration index (i.e., size), nor the position in the color-color diagram alone is completely successful in separating stars and clusters. What if we use a combination of both criteria? Figure 6 ($M_{\text{bol}}$ vs. $\log T_e$ diagrams for candidate massive stars around Knot S) shows that this appears to work fairly well. Using either the size or color criteria alone implies the existence of stars that are more massive than the stellar tracks (two upper panels in Figure 6). However, if we use both criteria simultaneously, all the remaining objects are consistent with being normal stars. We might note that this also suggests that there is an upper limit to the maximum mass of a star, since we would
expect more massive stars in such a large sample of stars if the stellar IMF was a simple power law (see Weidner & Kroupa 2006; Elmegreen 2005; and Figer 2005 for detailed treatments of this issue). This result should be considered tentative, however, pending a more careful look at other knots in the Antennae galaxies, and the development of Monte-Carlo simulations that will allow us to more quantitatively determine the statistical significance of the result.

5. The big picture—A general framework for understanding the demographics of stars and star clusters

The most extreme super star clusters, with magnitudes $M_V \approx -17$ and masses $\approx 10^8 M_\odot$, are found in merging galaxies. One might therefore assume that there is something special about the physical environment in these galaxies that makes it possible to form such massive clusters there, but nowhere else. This suggests that there may be two modes of star cluster formation: one for relatively quiescent galaxies, such as normal spiral galaxies, and one for starbursting galaxies (e.g., Gallagher 2004). However, the discovery of super star clusters in spiral galaxies by Larsen & Richtler (1999)—and the subsequent demonstrations by Whitmore (2003; originally presented in 2000 as astro-ph/0012546), and Larsen (2002)—that there is a continuous correlation between the magnitude of the brightest cluster and the number of clusters (e.g., Figure 10 from Whitmore 2003), suggests that there may be a single universal mode of star cluster formation, with the correlation simply being due to statistics. Hence, mergers and starburst galaxies may have the brightest clusters only because they have the most clusters. Several recent papers (e.g., Hunter et al. 2003) have also realized that it is important to take this “size-of-sample” effect into consideration when interpreting results.

Similarly, there may be a universal power law relationship for the disruption rate of clusters. For example, Fall et al. (2005) find that roughly 90% of the clusters in the Antennae are removed from the sample each decade of log time (i.e., a power law with index $-1$). Whitmore, Chandar, & Fall (2006) show that this relationship appears to be the same for the Antennae, the SMC (data from Rafelski & Zaritsky 2005), and the Milky Way (Lada & Lada 2003).

These two results have motivated us to develop a general framework for understanding the demographics of both star clusters and the field stars, which we assume are formed as a by-product of the disrupted clusters (Whitmore 2004; Whitmore, Chandar, & Fall 2006). The ingredients for the model are:

1) a universal initial mass function (power law, index $-2$);
2) various star (cluster) formation histories that can be coadded (e.g., constant, Gaussian, burst, ...);
3) various cluster disruption mechanisms (e.g., $\tau^{-1}$ for <100 Myr, i.e., infant mortality; constant mass loss for >100 Myr, i.e., 2-body relaxation); and
4) convolution with observational artifacts and selection effects.

This simple model allows us to predict a wide variety of properties for the clusters, field stars, and integrated properties of a galaxy. Of particular relevance for the present paper is the agreement between prediction and observations of what fraction of the UV light emitted by clusters (see discussion in §3). Figure 7 shows how the fraction of mass in clusters and in field stars varies as a function of time for our best-fitting model of the Antennae. We plan to extend this treatment to a number of other nearby galaxies including M51, M101, and M82 (Chandar & Whitmore 2006).

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Figure 7. Fraction of mass in clusters and in field stars as a function of time for our Antennae model. See text for details.

of projects that are mentioned in this review, in particular, Rupali Chandar, Francois Schweizer, Mike Fall, Qing Zhang, and Barry Rothberg.

REFERENCES

Amram, P., Marcelin, M., Boulesteix, J., & Le Coarer 1992 *A&A* 266, 106.
Bastian, N. & Goodwin, S. P. 2006 *MNRAS* 369, 9.
Bruzual, A. G. & Charlot, S. 2003 *MNRAS* 344, 1000.
Cervino, M., Valls-Gabaud, D., Luridiana, V., & MASS-Hesse J. M. 2002 *A&A* 381, 51.
Chandar, R. & Whitmore, B. C. 2006 (in preparation: Paper 2).
Chandar, R., Leitherer, C., Tremonti, C. A., Calzetti, D., Aloisi, A., Meurer, G. R., & de Mello, D. 2005 *ApJ* 628, 210.
de Grijs, R., Parmentier, G., & Lamers, H. J. G. L. M. 2005 *MNRAS* 364, 1054.
de Wit, W. J., Testi, L., Palla, F., & Zinnecker, H. 2005 *A&A* 437, 247.
Elmegreen, B. G. 2005. In *Starbursts: from 30 Doradus to Lyman Break Galaxies* (eds. R. de Grijs & R. M. Gonzalez Delgado). ASSL Vol. 329, p. 57. Springer.
Fall, S. M. 2004. In *The Formation and Evolution of Massive Young Star Clusters* (eds. H. J. G. L. M. Lamers, L. J. Smith, & A. Nota). ASP Conf. Ser. 322, p. 399. ASP.
Fall, S. M., Chandar, R., & Whitmore, B. C. 2005 *ApJ* 631, L133.
Figuer, D. 2005 *Nature* 434, 192.
Gallagher, J. 2004. In *The Formation and Evolution of Massive Young Star Clusters* (eds. H. J. G. L. M. Lamers, L. J. Smith, & A. Nota). ASP Conf. Ser. 322, p. 411. ASP.
Holtzman, J. A., et al. (the WFPC team) 1992 *AJ* 103, 691.
Humphreys, R. M. 1983 *ApJ* 269, 335.
Hunter, D. A., Elmegreen, B. G., Dupuy, T. T., & Mortonson, M. 2003 AJ 126, 1836.
Jog, C. & Solomon, P. M. 1992 ApJ 387, 152.
Kumai, Y., Hashi, Y., & Fujimoto M. 1993 ApJ 416, 576.
Lada, C. J. & Lada, E. A. 2003 ARA&A 41, 57.
Larsen, S. S. 2002 AJ 124, 1393.
Larsen, S. S. & Richtler, R. 1999 A&A 345, 59.
Larsen, S. S. 2005. In Planets to Cosmology: Essential Science in Hubble’s Final Years (ed. M. Livio). Cambridge University Press.
Maíz-Apellániz, J. 2004 PASP 116, 959.
Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995 AJ 110, 2665.
Rafelski, M. & Zaritsky, D. 2005 AJ 129, 2701.
Schweizer, F. 2004. In The Formation and Evolution of Massive Young Star Clusters (eds. H. J. G. L. M. Lamers, L. J. Smith, & A. Nota). ASP Conf. Ser. 322, p. 411. ASP.
Toomre, A. 1977. In The Evolution of Galaxies and Stellar Populations (eds. B. M. Tinsley & R. B. Larson). p. 401. Yale.
Ubeda, L., Maíz-Apellániz, J., & MacKenty, J. 2006 (in press).
Walborn, N. R., Barba, R. H., Brandner, W., Rubio, M., Grebel, E., & Probst, R. 1999 AJ 117, 225.
Weidner, C. & Kroupa, P. 2006 MNRAS 365, 1333.
Whitmore, B. C. 2003. In A Decade of HST Science (eds. M. Livio, K. Noll, & M. Stiavelli). p. 153. Cambridge University Press.
Whitmore, B. C., et al. 2006 (in preparation).
Whitmore, B. C. 2004. In The Formation and Evolution of Massive Young Star Clusters (eds. H. J. G. L. M. Lamers, L. J. Smith, & A. Nota). ASP Conf. Ser. 322, p. 411. ASP.
Whitmore, B. C., Gilmore, D., Leitherer, C., Fall, S. M., Chandar, R., Blair, W. P., Schweizer, F., Zhang, Q., & Miller, B. W. 2005 AJ 130, 2104.
Whitmore, B. C. & Schweizer, F. 1995 AJ 109, 960.
Whitmore, B. C., Zhang, Q., Leitherer, C., Fall, S. M., Schweizer, F., & Miller, B. W. 1999 AJ 118, 1551.
Whitmore, B. C. & Zhang, Q. 2002 AJ 124, 1418.
Zepf, S. E., Ashman, K. M., English, J., Freeman, K. C., & Sharples, R. M. 1999 AJ 118, 752.
Zhang, Q., Fall, M., & Whitmore, B. C. 2001 ApJ 561, 727.