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The Formation and Evolution of Young Star Clusters in the Antennae

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Abstract.
Five populations of young, massive, compact star clusters have been identified in the "Antennae galaxies", the nearest and youngest example of a prototypical merging galaxy. The brightest of these clusters have all the attributes expected of young globular clusters, hence allowing us to study the formation and evolution of globular clusters in the local universe. Comparisons between the different populations and a variety of multi-wavelength observations are providing new insights into the formation of the clusters. For example, the very red clusters originally identified by Whitmore and Schweizer (1995) appear to be the youngest population, just emerging from their dust cocoon. The cluster luminosity functions for a wide variety of galaxies (i.e., mergers, starbursts, barred galaxies, spirals) appear to follow a "universal" power law, with index ≈ -2. The primary difference between the different galaxies is the normalization, with roughly a tenfold increase in the number of clusters in merging and starbursting galaxies. Hence, the fact that the brightest clusters are in mergers may be largely a statistical result. Simulations are now showing how the initial power law distribution for the clusters will evolve toward the peaked distribution found for old globular clusters, via a combination of processes including two-body evaporation, disk shocking, and stellar mass loss.

1. Introduction

The discovery of young massive star clusters in merging and starbursting galaxies has provided new insights into the study of star clusters. The brightest of these clusters have all the attributes expected of globular clusters. The Antennae galaxies are the youngest and closest example in Toomre's (1977) list of prototypical mergers. Hence, these galaxies represent perhaps our best chance for understanding both the merger process and the formation of globular clusters.

This contribution will briefly describe the discovery and early results derived from the study of young clusters in merging galaxies, will then focus on the Antennae galaxies and evidence that the brightest of the young, massive, compact clusters are young globular clusters, and will then discuss three recent hot topics: 1) multi-wavelength observations of the Antennae, 2) the apparent universality of the luminosity function, and 3) the evolution of the luminosity

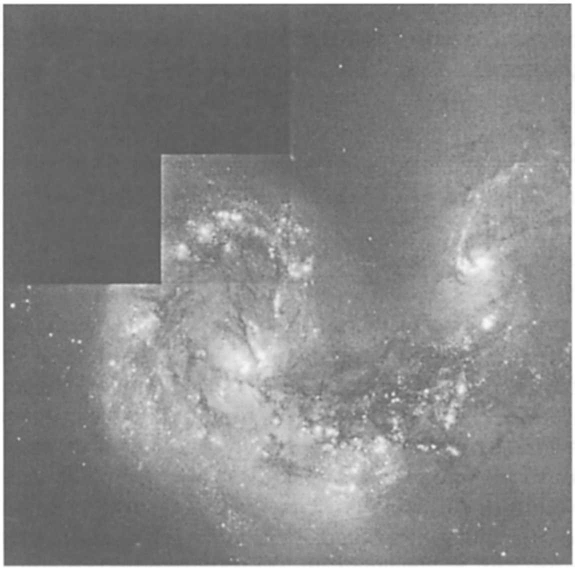

Figure 1. Image of the Antennae Galaxies (NGC 4038/4039) from Whitmore et al. (1999)

and mass functions. A more comprehensive review of the field, including a listing and details of other galaxies, can be found in Whitmore (2001).

2. Discovery and Early Results

A hint that young globular clusters might be formed in mergers was provided by Schweizer's (1982) observations of six unresolved bluish knots in the merger remnant NGC 7252. However, with so few objects he could not be sure they were not simply field stars. Lutz (1991) observed roughly a dozen blue point-like objects in the merger remnant NGC 3597, but he was not able to resolve the objects, and hence could not be certain they were not associations or giant HII regions. The HST observations of about 60 blue compact clusters in NGC 1275 (the central cD galaxy in the Perseus cluster) by Holtzman et al. (1992) was the primary catalyst in this field. Unfortunately, NGC 1275 is such a peculiar galaxy that it was not clear which of its peculiarities was responsible for the formation of the young clusters. Whitmore et al. (1993), using WFPC1 observations of the prototypical merger remnant NGC 7252 (Toomre 1977), found a population of about 40 blue point-like objects with luminosities and colors nearly identical to those found in NGC 1275. Whitmore & Schweizer (1995) followed this up with pre-refurbishment observations of another prototypical merger, NGC 4038/4039 (the "Antennae" galaxies, see Figures 1) with over 700 young star clusters. Subsequent observations of both these galaxies using WFPC2 (NGC 7252 - Miller et al. 1997; NGC 4038/4039 - Whitmore et al. 1999) have increased the numbers of cluster candidates tenfold.

In total, roughly 30 gas-rich mergers have now been observed with HST. In all cases young, massive, compact clusters have been observed, the brightest of which have the luminosities, colors, sizes, masses, distributions and spectra that are expected for young globular clusters (see Whitmore 2001 for a recent review).

3. Identification of Five Populations in the Antennae

The ability to accurately age-date the clusters in the Antennae plays a central role in our ability to piece together the evolutionary history of the clusters. In addition, by identifying the location of the youngest clusters we are able to determine what environmental conditions are necessary for their formation.

A variety of different techniques are available for measuring the ages of the clusters, including color-magnitude diagrams, color-color diagrams (and their relatives the reddening-free Q parameter diagrams), H_α strength and morphology, and spectroscopy. IR spectroscopy is especially valuable due to the dusty environments around many young clusters. Figure 2 shows how the color-color diagrams and reddening-free Q parameters can be used for age-dating clusters. This also provides an independent means of solving for the age and the reddening caused by dust. See Whitmore (2001) for a more complete review on the methods involved in age dating.

Using the the various techniques outlined above, we are able to identify five populations of star clusters in the Antennae.

The youngest clusters appear to be very red objects (the R sample; $\lesssim 5$ Myr), which Whitmore & Schweizer (1995) suggested are only now emerging from their dust cocoons. Several of these have recently been identified as strong IR sources (Vigroux et al. 1996, Wilson et al. 2000). Most of the R clusters are in the overlap region between the two galaxies. We will return to these red clusters in §4.

The second population of clusters (the B1 sample; 1 - 20 Myr) have ages based on the Q-Q analysis from Whitmore et al. (1999). While many of these clusters are in the overlap region, larger fractions are found in the Western Loop and Northeastern Star Formation regions. These clusters show very strong correlations with H_α flux, as expected.

The third population (the B2 sample; ≈ 100 Myr) has also been identified using the Q-Q analysis. The majority of these clusters are in the Northeastern Star Formation region. These clusters show much weaker H_α emission than the B1 sample.

The fourth population consists of intermediate-age clusters (the I sample; ≈ 500 Myr) which presumably formed during the initial encounter that produced the tidal tails. The clusters are quite widely dispersed, with most of their members in either the Northwestern Extension (see Figure 5 in Whitmore et al. 1999) or along the outer edge of the Northeastern Star Formation region as it leads into one of the tidal tails. While the R, B1, and B2 populations appear to be associated with a continuous episode of cluster formation, the I population appears to originate from a separate episode. Figure 17 in Whitmore et al. (1999) shows how clearly this population can be distinguished from the younger populations based on the color-color and Q-Q plots.

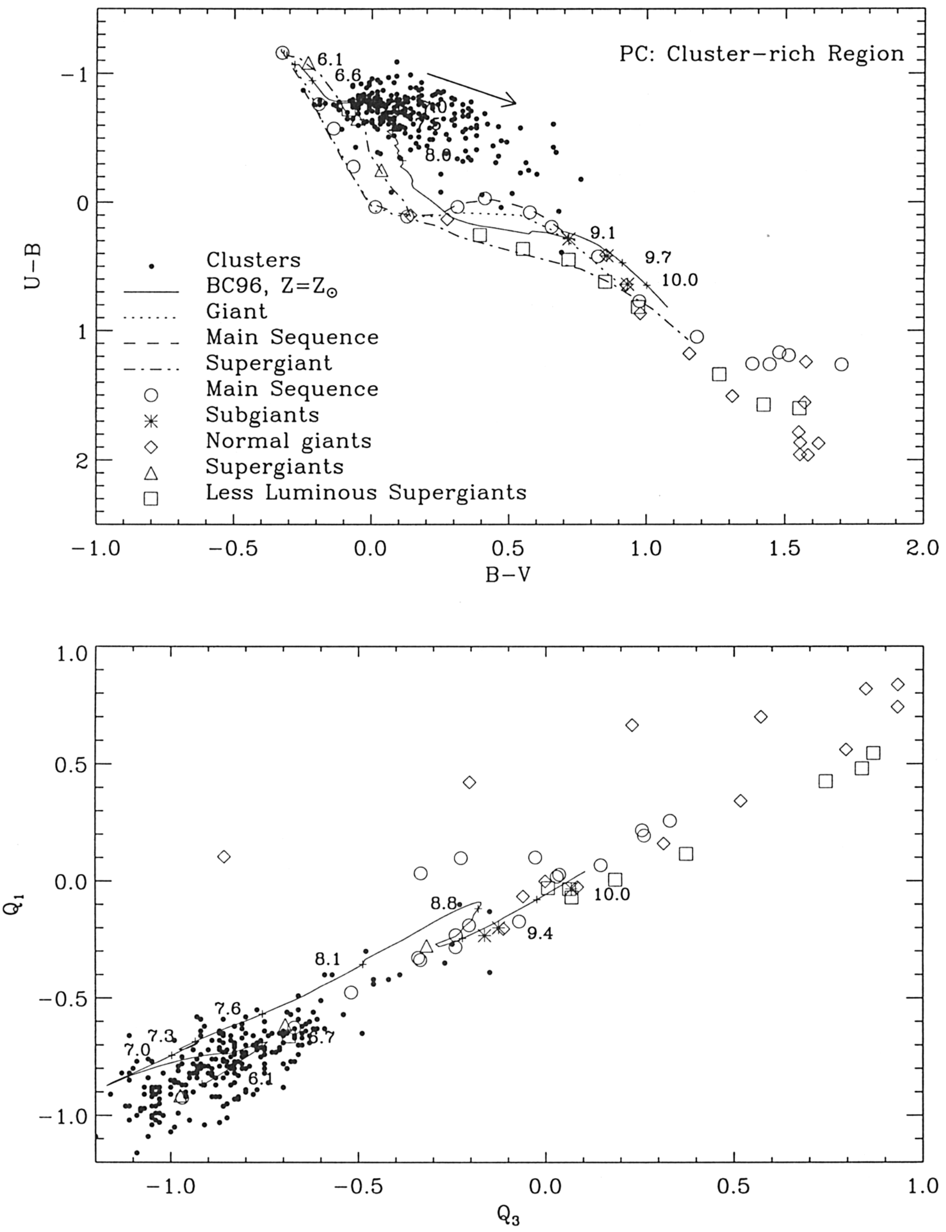

Figure 2. Color-color diagram and reddening-free Q parameter diagram for a cluster-rich region of the Antennae, populated primarily by clusters from the B1 sample. The numbers on the plots are the values of log(age). See Whitmore et al. (1999) for details.

The fifth population consists of old globular clusters (the O sample; ≈ 15 Gyr) which were preexisting in the two spiral galaxies before they collided. These clusters are most easily found in NGC 4039, due to the smaller numbers of bright young clusters that make it difficult to find these relatively faint clusters. Whitmore et al. (1999) list 11 candidates for old globular clusters in the Antennae.

4. Insights from Multi-Wavelength Studies of the Clusters in the Antennae

Following the discovery of young massive clusters, the Antennae has been the focus of a full arsenal of state-of-the-art observations covering a wide range in wavelength (e.g., 21 cm line emission, 6 and 3.5 cm radio continuum, CO emission, far-infrared observations at 60, 100, 450 and 850 Å, mid-infrared observations at 10 and 15 microns, H_α and UVRI observations from HST, far-UV observations at 1500 Å and x-ray observations; see Zhang, Fall, & Whitmore 2001 for references and discussion). These observations provide a variety of new insights into the formation and evolution of the clusters.

For example, the strongest ISO source is actually coincident with WS80, one of the very red clusters first proposed by Whitmore & Schweizer (1995) as young clusters just emerging out of their dust cocoons. Wilson et al. (2000) find three separate molecular clouds around WS80, and suggest that cloud-cloud collisions may play an important role in cluster formation. However, the lack of similar morphologies for the other very red objects suggest that this may not be the universal mechanism.

Zhang, Fall & Whitmore (2001) have performed cross-correlations between the flux from the various wavelength bands and the positions of the R, B1, and B2 samples of clusters in the Antennae. They find that the red clusters are most closely associated with the CO and ISO flux, supporting the idea that they are formed from giant molecular clouds. They also find a weak correlation with the CO velocity gradients and H_α velocity dispersion. Strong correlations would be predicted by models where high velocity collisions between molecular clouds are responsible for the formation of the clusters (e.g., Kumai et al. 1993) The weakness of the correlation may indicate that this is not the primary trigger for cluster formation, or may just reflect the lack of adequate spatial resolution of the velocity observations.

The strongest correlations are found between the B1 clusters (≈ 1 - 20 Myr) and H_α strength (Figure 3). This is easily understood since the O and B stars needed to ionize the gas live ≈ 10 Myr. This demonstrates the fact that the Q-Q analysis can successfully isolate a population of clusters with ages ≈ 10 Myr based on UBVI colors alone, and shows that the technique can identify physically meaningful correlations.

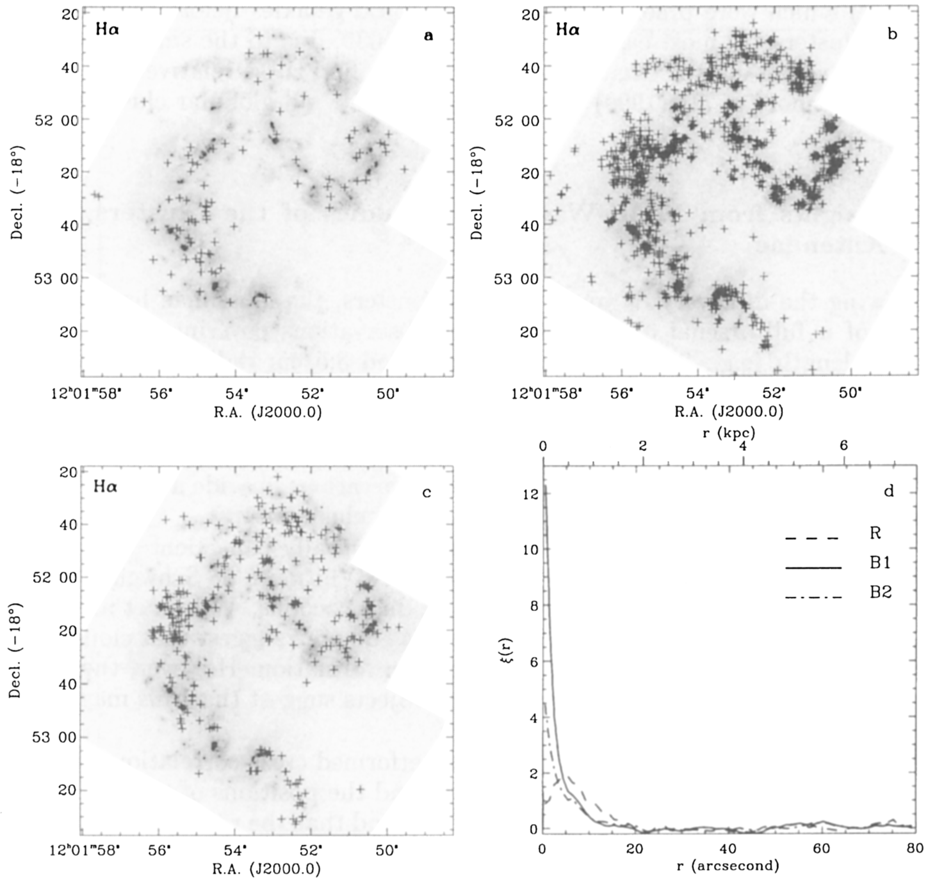

Figure 3. Comparison between locations of R, B1, and B2 samples (panels a, b, and c respectively) and H_α flux, and related cross-correlation functions (panel d). From Zhang, Fall, & Whitmore (2001).

5. Universality of the Cluster Luminosity Function ?

While it is clear that luminous young compact star clusters are produced in a wide variety of environments, they are observed in much greater number in mergers and starburst galaxies; systems where the most vigorous star formation is occurring. An important question is whether this is a statistical effect due to the lower number of clusters in galaxies with low star formation rates, or whether it is only possible to form the brightest and most massive young clusters in chaotic systems.

The situation may be analogous to the upper initial mass function in 30 Doradus. It was presumed that the large number of very luminous stars indicated that conditions in 30 Doradus were especially conducive for making high mass stars. However, Massey & Hunter (1998) find that the IMF is normal; that the large number of massive stars is simply due to the tremendous number of stars in the system and the young age of the cluster.

Figure 4a (from Whitmore 2001) shows a comparison of cluster luminosity functions which includes merging, starbursting, and barred spiral galaxies. He finds that all the luminosity functions have similar slopes, with an average power law index $\alpha = -1.93 \pm 0.06$ (uncertainty in the mean; the scatter is 0.18). The primary difference is the normalization of the luminosity function, with NGC 3256 and NGC 4038/39 having large numbers of clusters while NGC 3921 and HE 2-10 have relatively few clusters. There is no obvious trend for a cutoff at high luminosity for the more quiescent galaxies, suggesting a universal luminosity function is a reasonable approximation, albeit based on a small and nonuniform database.

Such an approach is oversimplified for a number of reasons, primary amongst them being that the luminosities of the clusters vary with time. For example, a single-age burst population will evolve to the right in Figure 4a, making it difficult to determine whether the luminosity function is lower because of evolution or due to a smaller number of clusters. Other difficulties with this simplistic approach are that it assumes similar star formation histories for the various galaxies, and ignores the fact that the faint end will probably undergo rapid evolution as the faint clusters dissolve (§6). Nevertheless, to first order the luminosity functions appear to be remarkably similar in form.

Another approach, which allows us to increase the sample at the expense of more scatter for any particular galaxy, is to plot the magnitude of the brightest cluster vs. the number of clusters in the galaxy, as shown in Figure 4b. We find a clear trend between the number of clusters observed and the magnitude of the brightest cluster. The solid line is the fit to the data (excluding NGC 1569) with a slope = -2.3 ± 0.2 . The dotted line shows the trend expected if there is a universal luminosity function with $\alpha = -2$ (i.e., a slope of -2.5 in Fig. 4b), and the increase in the luminosity is simply due to a larger sample of clusters. Again, to first order it appears that a universal luminosity function can explain the data, even with the large scatter expected from low number statistics, non-uniform databases, differences in selection criteria, and differences in cutoff magnitudes (only those with cutoffs $\approx$ -9 have been included).

These results support the idea, originally proposed by Larsen & Richtler (1999), that the formation of young, massive, compact clusters does not require a violent mode of star formation. It appears that the main difference between the mergers and more quiescent galaxies is that the amplitude of the luminosity function has been increased tenfold or more, hence statistically producing larger numbers of very luminous (and presumably massive) clusters which may survive the various destruction mechanisms and become globular clusters. The conditions required to make globular clusters may exist *globally* in mergers and starburst galaxies, but only *locally* in certain regions of barred and spiral galaxies, hence the smaller numbers of clusters. Perhaps this is how many of the disk globular clusters in spiral galaxies like our own Milky Way formed. Support for this idea comes from observations of M31 by Barmby & Huchra (2000), who find that the disk globular clusters may be younger than the halo clusters, with ages $\approx$ 8 Gyr.

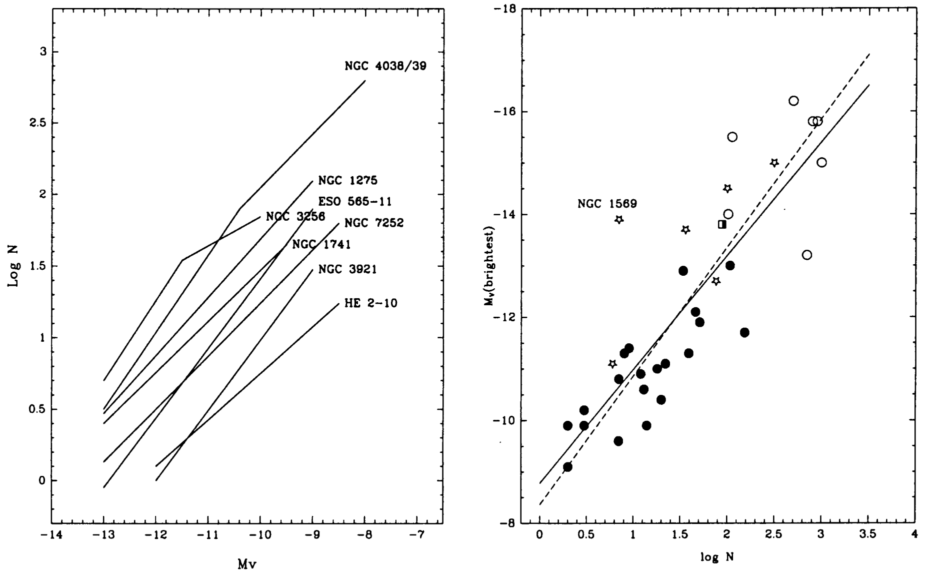

Figure 4. The left figure (4a) shows approximate luminosity functions for several merging and starbursting galaxies, normalized to have 0.25 mag bins (from Whitmore 2001). The right figure (4b) shows a plot of the magnitude of the brightest cluster vs. the log of the number of clusters. Filled circles are spiral galaxies from Larsen & Richtler (2000), open circles are mergers, stars are starburst galaxies, and the half filled square is a barred galaxy. The solid line is a best fit (excluding NGC 1569) while the dashed line is the prediction from a universal power law luminosity function with index $\alpha = -2$ (from Whitmore 2001).

It is easy to think of apparent counter examples to the universality of the cluster luminosity function. For example, NGC 1569 seems to stand out in Figure 4b, and may represent a special mode of massive cluster formation in dwarf starburst galaxies. However, one should keep in mind that the statistical deviations in galaxies with such small numbers of clusters will be very large, and NGC 1569 may represent the 1 in 100 dwarf galaxies with a 5 sigma deviation. The typical dwarf galaxy may be non-descript and hence unstudied.

Another possible counter example is our own Milky Way galaxy. While the predicted number of massive clusters currently being produced would be expected to be very small, since the star cluster formation rate is much lower than in merging and starbursting galaxies, over the age of the galaxy there should be at least some massive clusters being formed, and hence at least some young and intermediate age globular clusters. Where are they? One possibility is that some of the older more massive open clusters represent this population. Candidate open/globular clusters might include M67, Be 17 and Lynga 7, which according to Phelps et al. (1994), may be as old as the youngest globular clusters.

Perhaps some of the disk globular clusters, only a few which have been age dated too this point, will turn out to be members of this intermediate age population.

Another possibility is that spiral galaxies such as the Milky Way are only making massive clusters in locations that are not conducive to their long term survival. Examples might be the Arches and Quintuplet clusters near the center of the Milky Way (Figer et al. 1999). These are two young clusters with $\approx 10^4$ $M_\odot$ which are only expected to survive a few tens of Myr due to the strong tidal shear from the central black hole. Similarly, clusters formed in the plane of the galaxy may not last long due to frequent encounters with giant molecular clouds. Conversely, as discussed above, conditions appear to be globally conducive to forming massive star clusters in merging galaxies. While most of these clusters are expected to be be destroyed (see §6), at least some of the clusters will be on orbits which allow them to survive, especially since violent relaxation will populate all available orbits.

6. Evolution of the Cluster Luminosity Function

To first order, the luminosity functions (hereafter LF) of young compact clusters in merging galaxies are power laws with index ≈ -2 (see §5). Similarities between the luminosity functions of young clusters, and the mass functions of giant molecular clouds, have led several groups to suggest that the progenitors of the young star clusters found in mergers are giant molecular clouds, and to propose various models for their formation (e.g., Jog and Solomon 1992, Harris & Pudritz 1994, Schweizer et al. 1996, Elmegreen & Efremov 1997).

The power law LFs for young clusters are markedly different than the Gaussian profiles found for old globular clusters (e.g., Figure 3 of Zhang and Fall 1999,). However, various destruction mechanisms (e.g., 2-body evaporation, bulge and disk shocking, dynamical friction, stellar mass loss) should modify the distribution with time. Two-body evaporation appears to be the strongest amongst these mechanisms, destroying the fainter and more diffuse clusters first, and in certain conditions, leaving a peaked distribution similar to what is seen for old globular clusters (e.g., Fall and Zhang, 2001).

The destruction of a large fraction of the clusters begs the question, "What fraction of all stars are formed in compact star clusters?". Roughly 20 % of the UV light in merging and starbursting galaxies comes from young compact star clusters (Meuer 1995). In addition, as outlined above, many of the clusters will rapidly dissolve, hence the fraction of stars that were originally in clusters may be much higher than 20 %. The rapid destruction of most clusters would also explain the fact that in most of the recent mergers and starbursts where the clusters have been age-dated, the largest population of clusters are those with ages < 20 Myr. The alternative, that all these systems happen to be caught during a major burst, seems unlikely.

As an illustrative example, if we assume that the Antennae has been making clusters at roughly the same rate for the past 200 Myr, we can use figure 2 from Zhang and Fall (1999) to show that for every 20 clusters originally formed, only one will survive to an age of ≈ 100 Myr. While this crude calculation may not be justifiable for a single galaxy, which we may be catching during a burst, once a larger sample becomes available a more careful calculation of this sort can be made. In any case, it is clear that many of the clusters formed in mergers and starbursting galaxies will be destroyed, and the stars will join the field population.

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References

Barmby, P., Huchra, J. P. 2000, ApJ, 531, 29

Elmegreen, B. G. & Efremov, Y. N. 1997, ApJ, 480, 235

Fall, S. M. & Zhang, Q. 2001, ApJ, submitted

Figer, D. F., Kim, S. S., Morris, M., Serabyn, E., Rich, R. M., & McLean, I. S. 1999, ApJ, 525, 750

Jog C. & Solomon 1992, ApJ, 387, 152

Harris, W. E. & Pudritz, R. E. 1994, ApJ, 429, 177

Holtzman, J. A. et al. (the WFPC team) 1992, AJ, 103, 691

Kumai, Y., Hashi, Y., & Fujimoto, M. 1993, ApJ, 404, 144

Larsen, S. S. & Richtler, T. 1999, A&A, 345, 59

Lutz, D. 1991, A&A, 245, 31

Massey, P. & Hunter, D. 1998, ApJ, 493, 180

Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., & Garnett, D. R. 1995, AJ, 110, 2665

Miller, B. W., Whitmore, B. C., Schweizer, F., & Fall, S. M. 1997, AJ, 114, 2381

Phelps, R. L., Janes, K. A. & Montgomery, K. A. 1994, AJ, 107, 1079

Schweizer, F. 1982, ApJ, 252, 455

Schweizer, F., Miller, B., Whitmore, B. C., & Fall, S. M. 1996, AJ, 112, 1839

Toomre, A. 1977 *The Evolution of Galaxies and Stellar Populations,* ed. B. M. Tinsley & R. B. Larson (Yale, New Haven) 401

Vigroux, L. et al. 1996, A&A, 315, L93

Whitmore, B. C. 2001, astro-ph/0012546

Whitmore, B. C., & Schweizer, F. 1995, AJ, 109, 960

Whitmore, B. C., Schweizer, F., Leitherer, C., Borne, K., & Robert, C. 1993, AJ, 106, 1354

Whitmore, B. C., Zhang, Q., Leitherer, C., Fall, S. M., Schweizer, F. & Miller, B. W. 1999, AJ, 118, 1551

Wilson, C. D., Scoville, N., Madden, S. C., and Charmandaris, V. 2000, ApJ, 542, 120

Zhang, Q. & Fall, S. M. 1999, ApJ, 527, L81

Zhang, Q., Fall, M., Whitmore, B. C 2001, ApJ, in press

Discussion

B. Brandl: You mentioned the ISO peak of mid-IR emission. People have found extinctions of A_V 7 – 70 in the overlap region, which is quite substantial and could be corrected for by dereddening. In many cases - almost like in Arp 220 - one may just see the surface. This problem shouldn't affect the clusters that you've analysed, but there may be a lot more happening and many clusters may be hidden in the Antennae, which we just can't tell from the WFPC2 images.

B. Whitmore: Essentially all of the ISO peaks have optical counterparts, either relatively unreddened (e.g. $A_V \sim 1$) such as regions B and C, or highly reddened cluster like WS 80 ($A_V \sim 4$, Mengel). You suggest that perhaps WS 80 is not the true counterpart of the strongest ISO peak. This seems extremely unlikely, since the positional correspondence is perfect, and WS 80 stands out amongst the highly reddened clusters as one of the largest, as if we are just heats the dust over a wide region, hence explaining the high ISO flux. Since we clearly see WS 80 in V and even B, we know A_V is not 70. However, I agree that the heavy obscuration in some regions of the overlap region can cause problems, and for this reason we exclude the overlap region from most of our analysis. There may well be even more clusters in the Antenae, but probably not dramatically more since most of the CO, IR and 6cm peaks are already accounted for by optical counterparts. I certainly agree that IR observations will be very valuable for future work however.

H. Zinnecker: What do all these correlations, in particular the cluster luminosity function, tell us about the cluster formation process per se?

B. Whitmore: I did not talk about that too much since I believe Elmegreen and Schweizer will be talking about that in more detail. However, briefly, the fact that the luminosity function (and mass function, see Zhang and Fall, 1999) is a power law with index ≈ -2, which is the same as for giant molecular clouds, suggests that all we need to do is trigger the existing GMCs to collapse and form clusters. The high interstellar pressure expected in mergers and starbursts may provide this trigger (Elmegreen & Efrenov, 1997, Jog & Solomon).

J. Melnick: It is amazing that the "fractal" slope of the cluster MF obtains even in ISM as violent as the antennae. This strenghtens, in my opinion, the view that the ISM is in the state denominated self-organized criticality by complexity theory and that it is very resistent.

S. Kassin: Have you analyzed background light from the galaxy? This is very difficult to get at with spectra.

B. Whitmore: We did in our 95 paper using WFPC1 but we have not looked in detail yet for our newer WFPC2 data. It would be interesting to do this to compare with your own ground-based results.