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Massive star clusters in dwarf starburst galaxies

Göran Östlin

Institut d'Astrophysique de Paris, 98bis Boulevard Arago, F-750 14 Paris, France

Present address: Stockholm Observatory, SE-133 36 Saltsjöbaden, Sweden

Abstract. I will discuss the presence of massive star clusters in starburst galaxies with an emphasis on low mass galaxies outside the local group. I will show that such galaxies, with respect to their mass and luminosity, may be very rich in young luminous clusters.

1. Introduction

During the last decade, the study of young massive stellar clusters, sometimes referred to as super star clusters (SSCs) has seen rapid progress. From a few known examples of "blue populous clusters" in the Large Magellanic Cloud (LMC) and SSCs in the star forming dwarf galaxies NGC 1705 (Melnick, Moles, & Terlevich 1985) and NGC 1569 (Arp & Sandage 1985), the numbers have grown, largely thanks to HST. SSCs have now been found in a variety of different environments, as have globular clusters (GCs) which are *old* massive clusters. In this paper I will review the massive cluster content of, in particular, low mass starburst galaxies like blue compact galaxies (BCGs). A review of massive clusters in starbursts naturally becomes biased towards young SSC like objects. However, such galaxies may indeed contain also rich populations of older clusters.

The study of SSCs in starburst galaxies gained momentum with the advent of the HST. Ultraviolet imaging with the aberrated HST/FOC (e.g. Meurer et al. 1995, Conti and Vacca 1994) of starbursts revealed that a significant fraction of the star formation activity took place in SSCs. Meurer et al. (1995) studied nine galaxies, finding SSCs in most of them. Several other starbursts have been imaged with the aberrated HST/FOC (e.g. Conti et al., unpublished) and SSCs are frequently encountered. Optical imaging with the aberrated HST has also discovered SSCs in many low mass starburst galaxies (e.g. Hunter et al. 1994). The greater sensitivity of WFPC2 as compared to FOC has multiplied the number of detected clusters in ESO 338-IG04 (Östlin, Bergvall, & Rönnback 1998) and He 2-10 (Johnson et al. 2000).

In giant galaxies there seems to be several ways to form SSCs/GCs, e.g. mergers (see Miller 2000), and bars (e.g. Kristen et al. 1997) and circum-nuclear rings in spiral galaxies (e.g. Barth et al. 1995). There are even indications of SSC formation in the discs of normal spirals (Larsen & Richtler 1999). In low mass galaxies some of these mechanisms, e.g. formation of SSCs in bar and resonant induced density enhancements, are not available. Mergers are certainly producing SSCs in some low mass galaxies (e.g. ESO 338-IG04, ESO 350-IG38, ESO 185-IG13), but there might be other mechanisms too. The origin of active star formation in galaxies like NGC 1569 and NGC 1705 are not yet well understood. There are also dwarf stabursts which do not contain luminous SSCs (e.g. IC10, see Grebel 2000).

Cluster destruction mechanisms (e.g. due to tidal shocks) are weaker in low mass galaxies giving SSCs a greater chance of survival. In ESO 338-IG04 the dominant GC population is ~ 3 Gyr old, and this population alone is enough to classify the galaxy as GC rich in terms of specific frequency. Low mass galaxies are in general metal-poor (typically [O/H]~ -1, Kunth & Östlin 2000), which make them suitable for comparison with high redshift conditions and early GC formation. Dwarf galaxies have certainly been important ingredients in the hierarchial buildup of massive galaxies. Another virtue is that internal extinction in general is small, which for instance makes age dating more secure.

Thus, dwarf starbursts are good places to investigate the formation and evolution of massive star clusters. Even if one cannot be sure whether a SSC will evolve into a bona fide GC or dissolve, a proto-GC must look very much like a SSC (Kennicutt & Chu 1988) and the collective formation of a few SSCs will, by necessity, be associated with a starburst. Thus populations of GCs and survived SSCs trace former starbursts, and may be used to study the evolution of galaxies. For example, if the excess of faint blue galaxies seen in deep optical counts is due to starbursts originating in merging galaxies at intermediate redshift, one would expect these to form significant numbers of SSCs/GCs which should be visible as intermediate age GC populations in local galaxies.

2. SSC richness in galaxies

The richness of GCs in galaxies is often parametrized by the specific frequency, S_N, which is the number of GCs divided by the host galaxy luminosity (Harris & van den Bergh 1981). If counting only luminous clusters ($M_V \leq -11$) and relating to $M_{V,host}$, the total absolute V magnitude of the host galaxy, one may define a specific frequency of luminous SSCs: $S_{11} = N_{11} \times 10^{0.4(M_{V,host}+15)}$, where N_{11} is the number of clusters with $M_V \leq -11$. S_{11} will be independent of the assumed distance to a galaxy, and will be biased towards young massive clusters. The luminosity limit excludes contamination by supergiant stars and makes it possible to compare galaxies at different distances studied at different depth.

In Table 1, S_{11} is given for a selection of galaxies of different types, where N_{11} can be obtained with reasonable accuracy (in nearby galaxies like M82 the large angular extent makes it difficult to estimate N_{11}). The table is by no means complete (see e.g. Miller 2000, for more references). The N_{11} values do not take internal extinction in the galaxies into account, but since the same is true for $M_{V,host}$, this should be a second order effect. If the luminous SSCs follow a power law luminosity function, $\phi(L) \propto L^{\alpha}$, with $\alpha = -2$, S_{11} will be independent of the internal extinction as long as A_V is equal for the SSCs and the integrated galaxy light. This is not allways true since young SSCs may suffer from high local extinction. If $\alpha < -2$, internal extinction will effectively lower the observed S_{11} values. All values in Table 1 assume $H_0 = 75$ km/s/Mpc. The $M_{V,host}$ values were assembled from different sources including both accurate CCD photometry and photographic magnitudes. Many apparent total V-magnitudes have been taken, or estimated, from NED. Thus there might be an inhomogeneity on the 0.5 magnitude level (corresponding to 50% uncertainty on S_{11}), which one should be aware of when comparing galaxies.

Values $S_{11} \leq 0.5$ are found for giant mergers, while the luminous BCGs discussed below have $S_{11} \geq 0.6$. There are indications that these galaxies are actually dwarf mergers. The nearby star forming galaxies NGC 1569, NGC 1705 and NGC 1140, have intermediate S_{11} values. For LMC, no cluster is bright enough to qualify without correcting for internal extinction. Most nearby dwarf irregular (dI) galaxies with modest star formation do not contain luminous SSCs (see Grebel 2000). In the mergers, the number of luminous SSCs decrease with the estimated age of the merger remnant as was found by Schweizer et al. (1996).

Table 1. Specific frequency of luminous SSCs for a selection of galaxies ($H_0 = 75$km/s/Mpc). See text for more details.

Galaxy	Type	$M_{V,host}$	N_{11}	S_{11}	Source for N_{11}
ESO338-IG04	BCG	-19.3	53	1.0	Östlin et al. 1998
Mrk 930	BCG	-19.4	~110	1.9	This paper
ESO185-IG13	BCG	-19.7	~105	1.4	This paper
ESO350-IG38	BCG	-20.4	~130	0.9	This paper
He2-10	BCG	-18.3	12	0.6	Johnson et al. 2000
NGC 1705	Irr/BCG	-16.2	1	0.3	O'Connell et al. 1994
NGC 1569	Irr/BCG	-17.8	4	0.3	O'Connell et al. 1994
NGC 1140	Irr	-19.2	6	0.1	Hunter et al. 1994
NGC 1741	Merger	-20.9	~50	0.2	Johnson et al. 1999
NGC 7252	Merger	-22.1	~60	0.1	Miller et al. 1997
NGC 4038/4039	Merger	-22.1	~150	0.2	Whitmore et al. 1999
NGC 3921	Merger	-21.9	11	0.02	Schweizer et al. 1996
NGC 3256	Merger	-21.9	~280	0.5	Zepf et al. 1999
NGC 1275	Merger	-22.6	~75	0.07	Carlson et al. 1998

3. A few case studies

3.1. ESO 338-IG04 (= Tol 1924-416)

Ground based imaging had revealed an overdensity of faint blobs around this well known blue compact galaxy, which was the motivation behind HST/WFPC2 followup observations (Östlin et al. 1998). These observations revealed a starburst region composed of numerous blue star clusters and a swarm of surrounding GCs. In all, the number of star clusters (after correction for contamination by foreground stars, supergiant stars and background galaxies) is above 100 (completeness limit $M_V \approx -9$ to -10). Spectral synthesis modelling of U, B, V, I colors indicated the presence of distinct peaks in the cluster formation history. In addition to the ongoing event there are old (~ 10 Gyr) GCs, and in particular a very prominent population of intermediate age (2 to 5 Gyr old) GCs. This intermediate age population contains the most massive cluster candidates and among them an object (no. 34 in the outer sample of Östlin et al. 1998) with an estimated mass in excess of $10^7 M_\odot$ (for a variety of different IMFs). ESO 338-IG04 is an intrinsically luminous ($M_V = -19.3$) metal poor ([O/H]$= -1$) BCG. The dynamics and morphology suggest that the galaxy is the product of a dwarf galaxy merger (Östlin et al. 1999, 2000). The current specific frequency, $S_N = 2$, is predicted to rise to $S_N \geq 10$ in one Gyr as the starburst ceases and fades. The most luminous SSCs were found already by Meurer et al. (1995).

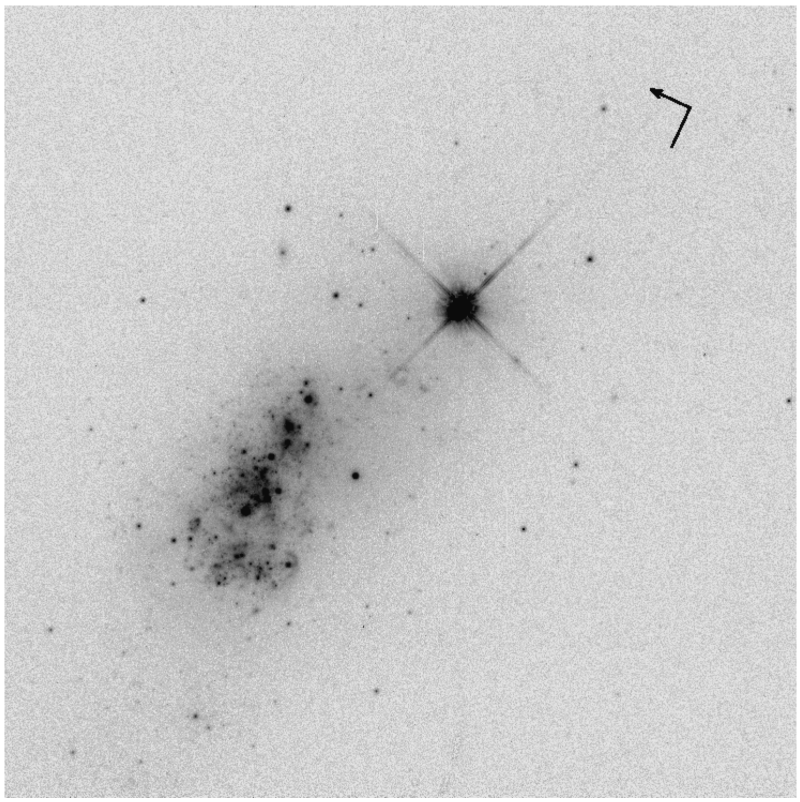

Figure 1. ESO 338-IG04 imaged through filter F814W with the Planetary Camera of HST/WFPC2. The image size is $33'' \times 33''$. North is up-left (arrow head), east is down left. The length of the arrow is $1.8''$, corresponding to ~ 330 pc at a distance of 37 Mpc. The bright source $\sim 5''$ west of the centre of the image is a foreground star.

3.2. He 2-10 (= ESO 495-G21)

HST/FOC observations of He2-10 revealed "knots", some of which appeared to be resolved with diameters < 10 pc (Conti & Vacca 1994). It was suggested that these might be young GCs, but the use of a single UV passband made it hard to say more (e.g. addressing masses) than that the objects were young. More recent WFPC2 observations (Johnson et al. 2000) confirm the FOC results, and multiply the detected number of clusters by reaching fainter and redder objects. The faint, red objects may be intermediate age GCs or reddened SSCs. The galaxy is one of the most nearby BCGs and a candidate dwarf merger.

3.3. Markarian 996

Markarian 996 is a blue compact dwarf ($M_V = -17.2$) with regular elliptical outer isophotes and intense star formation in a very compact central HII region (Thuan, Izotov, & Lipovetsky 1996). The central HII region is bright enough to saturate the WFPC2 images, but it could be a luminous ($M_V \lesssim -12$) young SSC. Intereestingly there are plenty of old GCs, asymetrically distributed around Mrk 996, with a luminosity function similar to that of Galactic GCs. Mrk 996 is, together with ESO 338-IG04, one of the rare known examples of a BCG posessing an old GC population. Mrk 996 has a GC specific frequency $S_N > 5$, similar to low-luminosity/dwarf ellipticals (Miller et al. 1998).

4. The Malkan et al. (1998) snapshot survey of AGN

Malkan, Gorjian, & Tam (1998) conducted an HST/WFPC2 snapshot survey of AGN, but included also a comparison sample consisting of 50 galaxies classified as having HII-activity. These "HII" galaxies can be divided in two broad classes: irregular galaxies and spiral galaxies with nuclear star formation.

Of galaxies having irregular or distorted morphology 3/4 appears to contain at least a few SSCs, while only 1/3 of the spirals do. Galaxies classified as irregular here are generally rather luminous and not typical dI galaxies like those in the local group. It is anyway obvious that the irregular galaxies, in view also of a lower average luminosity, appear to be more efficient SSC formers than spirals. Part of this effect could be explained by higher average extinction in spirals than irregulars. The survey used only one pass band (F606W) and rather short exposures which were not cosmic ray split, making it of limited use for quantitative studies. However, luminous SSCs can be easily identified and approximate photometry may be otained from archive images.

The survey includes ESO 185-IG13 and ESO 350-IG38 which have been studied dynamically by Östlin et al. (1999,2000). Both dynamics and morphology give strong support for a merger induced origin of the strong starbursts seen in these galaxies, which have similar properties to ESO 338-IG04. These galaxies are also among the most cluster rich in the whole survey. Extracting photometry for the SSCs in the HST archive images results in $S_{11} = 0.9$ and $S_{11} = 1.5$ for ESO 350-IG38 and ESO 185-IG13 respectively, see Table 1. ESO 350-IG38 contains several SSCs with $M_V \sim -15$.

Another example, perhaps the best one in the whole survey, of a very SSC rich starburst is Mrk 930, for which $S_{11} = 1.9$, see Table 1. Also Mrk 930 has a very irregular morphology. The Malkan et al. (1998) survey also has a few objects in common with the study of Meurer et al. (1995).

5. Conclusions and Perspectives

Among dwarf and low mass galaxies we encounter both galaxies that appear to be very efficient formers of massive clusters, and galaxies that appear totally devoid of such objects.

Some luminous BCGs have specific frequncies of luminous ($M_V \leq -11$) SSCs $S_{11} \geq 1$, which is an order of magnitude larger than most of the prototypical SSC factories: the "Antennae", NGC 7252 and NGC 1275. Thus there is a tendency for S_{11} to increase when going to low mass starburst galaxies. A similar trend has been found for the specific frequency of GCs among dwarf ellipticals (Miller et al. 1998). The purpose of comparing S_{11} values was to show that low mass, metal-poor, starburst galaxies are excellent hunting grounds for luminous SSCs, and in addition problems with extinction are much smaller than in giant mergers. The BCGs with the highest S_{11} are believed to be the product of dwarf galaxy mergers (Östlin et al. 1999, 2000). A possible explanation to the higher S_{11} values is that the starburst timescales are shorter in systems with lower mass, whereas in a giant merger one expects a more extended starburst. There are also BCGs and low mass starbursts which do not contain luminous SSCs. Although the expected number of SSCs in galaxies of very low luminosity will always be small and subject to statistical fluctuations, there migh be a connection to the triggering mechanism of the starbursts. Merging dwarfs might be more efficient SSC formers than non-merging ones.

A couple of BCGs (ESO 338-IG04 and Mrk 996) in addition contains rich populations of older GCs. There is no a priori reason to believe that old GC systems are intrinsically rare among BCGs. Rather few BCGs have been studied at sufficient depth and spatial resolution to unveil faint old GCs. The properties of relatively old GCs in BCGs may provide important information about the nature of the host galaxy.

An unbiased survey of star forming dwarf galaxies with HST to characterize the frequency of star clusters, their colors and host galaxy properties, would allow to quantitatively study cluster formation in low mass galaxies. The Malkan et al. (1998) survey do not fullfil these criteria but show that such a program could be very rewarding. A better understanding of the ultimate fate of SSCs is also required. Dynamical mass estimates are still rare and often result in masses of the right order of magnitude but surprisingly low mass to light ratios (see Smith & Gallagher 2000). If this is due to flat or top heavy IMFs it would make it harder for young SSCs to survive and become GCs.

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Discussion

U. Fritze von Alvensleben: I wonder if the star clusters you see in dwarf galaxies could really be young globular clusters. Burst strengths and star formation efficiencies found for samples of blue compact dwarfs are $\lesssim 1$ %, whereas GC formation modelling by Brown et al. (1995, ApJ 440, 666) requires star formation efficiencies of $\geq 10\%$.

G. Östlin: What matters is really the local star formation efficiency (SFE) and not e.g. how large a fraction of the gas is converted into stars on a global scale. Moreover, the SFE limit ($\geq 10\%$) you refer to is the one required for a young GC to survive the Galactic tidal field, however tidal fields are weaker in low mass galaxies. But of course, formation of numerous young globular clusters would require high global SF efficiencies and burst strengths. This is also the case for the examples I am discussing, which all are galaxies with strong starbursts (i.e. the gas depletion timescale, and/or the timescale to build up the observed stellar mass is much shorter than a Hubble time). It is true that many galaxies termed "blue compact" in reality have very modest star formation rates, but it is not in these galaxies we predominantly find young GC candidates.

J. Gallagher: If most dwarfs make SSCs in reasonable numbers, why do we then see so few in WFPC2 images of "normal" dI galaxies? - Isn't this a problem?

G. Östlin: Normal dIs have mostly "normal" star formation rates with respect to the mass of the galaxy and are not experiencing starbursts (in terms of star formation timescales, see previous comment). Moreover, their luminosities are often so low that we would not expect many SSCs if they had the same specific frequency of SSCs as e.g. ESO338-IG04 or giant mergers. Nevertheless, it may be that formation of bound clusters require special conditions (like high pressure or gas densities) which are not fulfilled in dwarfs except in the case of external triggers, e.g. mergers and strong interactions. The SSC rich dwarfs discussed above have perturbed morphology and signs of mergers and/or interactions.