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Open, Massive and Globular Clusters – Part of the Same Family?

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Abstract. Populations of young star clusters show significant differences even among "normal" disk galaxies. In this contribution I discuss how properties of young cluster systems are related to those of their host galaxies, based on a recent study of clusters in a sample of 22 nearby spiral galaxies. Luminous young clusters similar to the "super" star clusters observed in starbursts and mergers exist in several of these galaxies, and it is found that the luminosity of the brightest star cluster as well as the specific luminosity of the cluster systems both correlate well with the host galaxy star formation rate. When considering star clusters in different environments the traditional distinction between "open", "massive" and "globular" clusters breaks down, underscoring the need for a universal physical description of cluster formation.

1. Introduction

It is becoming increasingly clear that "open" clusters as we know them in the Milky Way may not be a representative sample of young star clusters in galaxies in general. It has been known for many years that the Magellanic Clouds, and the LMC in particular, contain a number of young "populous" or "massive" clusters (hereafter YMCs) which have no counterpart in the Milky Way (e.g. Hodge 1961). Conversely, the apparent *paucity* of star clusters in the irregular dwarf galaxy IC 1613 has presented an equally puzzling case (van den Bergh 1979). The presence of exceedingly luminous "super star clusters" (SSCs) in the nearby starburst galaxy M82 was first pointed out by van den Bergh (1971). Similar objects in NGC 1569 and NGC 1705 were noted by Sandage (1978) and Arp & Sandage (1985), and more recently HST observations have revealed large numbers of SSCs in many starburst galaxies, most notably in mergers like e.g. the "Antennae", NGC 4038/4039 (Whitmore & Schweizer 1995). Although the presence of SSCs/YMCs is often linked to starburst activity, it is less clear why they are also present in some apparently normal galaxies (Kennicutt & Chu 1988). In this contribution I discuss the main results of a recent study of YMCs in a number of nearby late-type galaxies (mostly spirals), aiming at a better understanding of the differences between young cluster populations in different environments.

2. Data

UBVI and Hα CCD imaging data for 22 nearby, mildly inclined spiral galaxies were collected with the Danish 1.54 m telescope at ESO / La Silla, the 2.56 m Nordic Optical Telescope at La Palma, Canary Islands and with the 3 m Shane reflector at Lick Observatory. A YMC was defined as a point source without Hα line emission, $B - V < 0.45$, and with $M_V < -8.5$ for $U - B \geq -0.4$ and $M_V < -9.5$ for $U - B < -0.4$. These selection criteria ensure minimal contamination from Galactic foreground stars as well as individual luminous stars within the galaxies themselves. In some cases we were also able to reidentify our cluster candidates on archive HST images, confirming that most of the objects identified on the ground-based images were indeed young clusters (Larsen 2000). The adopted limit in $B-V$ corresponds to an upper age limit of about 500 Myr, but the sample is biased towards younger clusters because of their generally higher luminosities. In addition to our own ground-based observations, data for a number of other galaxies were compiled from the literature, forming the basis for a comparison of the young cluster systems in a wide variety of environments. Details about the data reduction procedures, cluster selection criteria and a list of the galaxies are given in Larsen & Richtler (1999; 2000).

3. Results

The 22 observed galaxies showed a wide variety in the properties of their cluster systems, with the number of YMCs in each galaxy ranging from a handful or less (e.g. NGC 45, NGC 247, NGC 300) to more than 100 (M83, NGC 6946). The left panel in Figure 1 shows the absolute V-band magnitude of the brightest cluster in each galaxy ($M_V^{\rm br}$) as a function of the host galaxy star formation rate (SFR), derived from IRAS far-infrared fluxes (Kennicutt 1998). The + markers indicate the 22 spiral galaxies, while the $*$ symbols denote literature data. The plot shows a well-defined correlation between $M_V^{\rm br}$ and the host galaxy SFR. Interestingly, even IC 1613 (data from Wyder, Hodge and Cole 2000) fits quite nicely into the relation. NGC 1569 and NGC 1705 represent possible outliers, although it should be noted that the cluster "systems" in each of these two galaxies are dominated by only 1 or 2 very bright clusters (O'Connell, Gallagher, & Hunter 1994).

From Figure 1, some galaxies evidently contain much more luminous clusters than others, with $M_V^{\rm br}$ ranging between -8.5 and -13 for the spirals. For comparison, the brightest known open clusters in the Milky Way have $M_V \sim -10$ (e.g. h and χ Persei, Schmidt-Kaler 1967) although a few even brighter clusters might hide in remote parts of the disk. Translating the M_V magnitudes to cluster masses is non-trivial because the mass-to-light (M/L) ratios are very sensitive to age, differences in the stellar IMF etc. For a Salpeter IMF extending down to 0.1 $M_\odot$, the V-band luminosity per unit mass changes by nearly four magnitudes between an age of 5 Myr and 500 Myr (Bruzual & Charlot 2001, in preparation), but for a typical cluster age of $\sim 20 \times 10^6$ years the $-8.5 < M_V < -13$ range corresponds to a mass range of very roughly $10^4\ M_\odot < M < 10^6\ M_\odot$.

A relation of the type shown in the left-hand panel of Figure 1 might be expected just from sample statistics, since galaxies with high SFRs will also tend

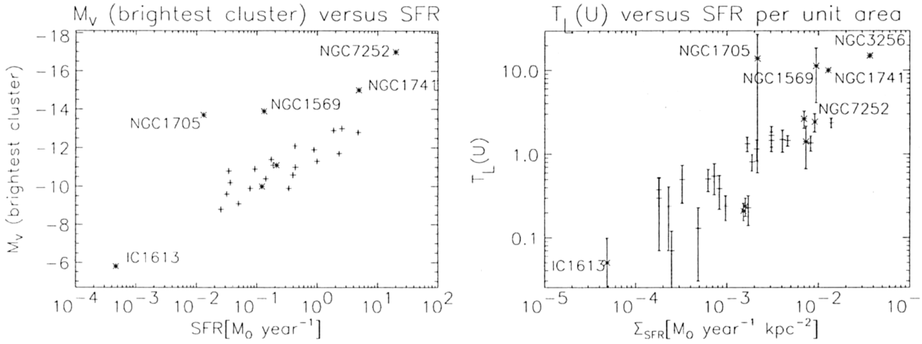

Figure 1. Left panel: The magnitude of the brightest cluster, $M_V^{\rm br}$ as a function of host galaxy star formation rate. Right panel: Specific luminosity, $T_L(U)$, versus area-normalised star formation rate $\Sigma_{\rm SFR}$.

to have larger numbers of clusters and the likelihood of encountering very luminous clusters is higher in richer cluster systems, unless the luminosity function is truncated. Another useful tool for studying young cluster populations, one that does not suffer from this effect, is the *specific luminosity*, defined as

$$T_L = 100\,\frac{L(\text{clusters})}{L(\text{galaxy})} \tag{1}$$

where L(clusters) is the total integrated luminosity of the cluster system and L(galaxy) is the luminosity of the host galaxy. Rather than using the specific *frequency*, as is customary in studies of old globular cluster populations, T_L has the advantage of being less sensitive to incompleteness effects because it is dominated by the brightest clusters. The right-hand panel of Figure 1 shows the U-band specific luminosity $T_L(U)$ (see Larsen & Richtler 2000), now as a function of the area-normalised star formation rates of the host galaxies ($\Sigma_{\rm SFR}$). Again, a quite well-defined correlation exists. As before, NGC 1569 and NGC 1705 have rather high $T_L(U)$ values for their star formation rates, but the large error bars that result from the poor statistics in these galaxies now make this deviation less striking. The general impression from the figure is that $T_L(U)$ increases steadily as a function of $\Sigma_{\rm SFR}$, with IC 1613 constituting one extreme endpoint of the relation, and active starbursts like NGC 1741 and NGC 3256 at the other.

4. Discussion

First of all, one notes that it is very difficult to make a meaningful division between galaxies with and without "massive" star clusters. Both $M_V^{\rm br}$ and $T_L(U)$ show a steady progression with the host galaxy SFR and it appears that massive clusters (according to anyone's preferred definition) form *whenever the host galaxy SFR is high enough.* Thus the very rich cluster systems in mergers and starburst galaxies are naturally explained as due to the very high SFRs there, and it is not necessary to invoke special mechanisms which operate only in these environments to explain the presence of very luminous, young clusters, other than those that triggered the starbursts in the first place.

Massive star clusters probably form a natural extension of the normal open cluster luminosity function (LF) to higher luminosities in galaxies with high SFRs, rather than being a distinct class of objects. In fact, van den Bergh & Lafontaine (1984) have shown that extrapolation of the Milky Way open cluster LF to brighter magnitudes would yield a total of $\sim$ 100 objects with $M_V = -11$, which is clearly incompatible with the observations. They thus suggested a drop-off in the Milky Way open cluster LF somewhere in the range $-11 < M_V < -8$. If this drop-off occurs at different magnitudes in different galaxies, this could strongly affect the number of massive young clusters. Although our ground-based data did not allow us to study the faint end of the LF for young clusters, some crude estimates show that the observed number of clusters with $-12 < M_V < -10$ in YMC–rich galaxies like M51 are compatible with quite normal populations of "open" clusters and extrapolation of the open cluster LF to higher luminosities (Larsen 2000).

The U-band specific luminosity is mostly sensitive to the light from young stellar populations, and is therefore likely to be an indicator of the relative fraction of stars forming in bound clusters, relative to field stars. One then finds that this fraction *increases* with the star formation rate, from less than 0.1% in galaxies like IC 1613 to more than 10% in active starbursts.

Eventually, understanding the formation of massive clusters will mean understanding the physical processes in the interstellar medium and molecular clouds in which they are born. In the Milky Way, star clusters generally form within Giant Molecular Clouds (GMCs) with masses up to a few times 10^6 $M_\odot$. Although GMCs potentially have enough gas to form quite massive clusters, cluster formation in the Milky Way is evidently an inefficient process. There are basically two ways to form higher-mass clusters: Either GMCs in other galaxies are somehow able to convert a higher fraction of their mass into bound star clusters, or clusters form with a constant efficiency in all galaxies and formation of YMCs requires larger molecular clouds than the Milky Way GMCs. The notion of such 'Super-GMCs' (SGMCs) was conceived by Harris & Pudritz (1994), originally with the aim of explaining the formation of old globular clusters in galactic halos, but we might now have a chance to test this idea by observing galaxies which are currently forming YMCs. A few high-resolution studies of CO gas have been carried out for M51, M83 and the Antennae (Rand, Lord, & Higdon 1999; Wilson et al. 2000), all of which are now known to contain rich YMC populations. These studies have indeed detected "Giant Molecular Associations" with masses of $10^7 - 10^8$ $M_\odot$, or 1 – 2 orders of magnitude higher than for Milky Way GMCs. Whether or not SGMCs are the birthsites of YMCs remains to be verified, and it is possible that these complexes might resolve into smaller subunits when examined at higher resolutions. In any case, more high-resolution studies of molecular gas in galaxies with YMC populations are likely to provide important insight into their formation.

5. Conclusions

- "Massive" clusters can form in many different environments. Although mergers represent one efficient way of providing the required high star formation rates, they are evidently not the only way to form massive clusters and processes that operate only in mergers or otherwise disturbed galaxies (like large-scale cloud-cloud collisions) are unlikely to be the primary mechanism responsible for YMC formation. It seems more likely that all star clusters (very likely even globular clusters in galactic halos) form by the same basic physical mechanism.

- The distinction between "open", "massive" and "super" clusters may turn out to be largely an artificial one. If we had been living in a different galaxy, chances are our classification of stellar clusters would have been different, too.

- $M_V^{\rm br}$ and $T_L(U)$ both increase gradually as a function of the host galaxy SFR. At one extreme of the relation are galaxies like IC 1613 with very low SFRs and correspondingly feeble cluster systems. At the other extreme are starbursts and merger galaxies with their very high SFRs and large numbers of highly luminous clusters. "Normal" galaxies fall in between these extremes, but still show significant variations in $M_V^{\rm br}$ and $T_L(U)$. Some nearby spirals like M51, M83 and NGC 6946 contain young clusters that are almost as luminous as those in the "Antennae" galaxies.

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Discussion

R. Kennicutt: If the SFR per unit area is the primary determinant of the massive cluster fraction, then you should see a strong concentration of massive clusters with radius within individual spiral galaxies (because the SFR/area falls off rapidly with radius in most spirals). This would provide a nice test of whether your relationship is physical, or otherwise is simply an artifact of a more fundamental correlation along the Hubble sequence.

S. Larsen: In most of the galaxies we have looked at there are not really enough clusters to say much about their radial distribution. In the few galaxies with many clusters, the surface density of cluster appears to follow the general disk surface brightness, although varying completeness is a major concern.

B. Elmegreen: If the nuclei of dE's originally were formed as globular clusters at larger galactocentric radii I suppose that you might expect to find some nuclei with metal abundances that are lower than those of the surrounding field stars. Do you think that this would provide any meaninful test of your hyphothesis?

S. Larsen: Yes. If dE nuclei form primarily from the merger of globular clusters then they should be relatively metal-poor. If they form instead from a nuclear starburst, they might be more metal-rich than the globular clusters and the underlying dE stellar population.

B. Elmegreen: If stars almost always form in dense clusters, as observed in the solar neighborhood, then the fraction of star formation currently in dense clusters in a region of star formation well depend on the ratio of dispersal time to formation time. Once you define a mass and radius then the dispersal time is given and the primary variable left is the formation time. So when the formation rate is high, then a large fraction of stars will still be in clusters, as your correlation shows. Thus your correlation might be more of a relative survival frequency than relative cluster formation frequency.

S. Larsen: The T_L probably measures the fraction of stars that form in clusters which are able to survive for "some" period of time. So it may well be that some of the T_L variations are due to differences in survival/disruption times. Still, it may be significant that the luminosity of the brightest cluster appears to increase with SFR although sampling effects certainly play a role. I would like to look more at the cluster luminosity function in different environments to see if there are real variations.

S. Zepf: One way to think about the "nomenclature" of types of clusters is that almost nothing with mass less than $10^5 M_\odot$ will survive for a Hubble time. About formation, an alternative to massive diffuse SGMCs is to increase the density and star formation of objects like normal GMCs. GMCs have roughly the right masses to make globulars, but are too diffuse and have low star formation efficiency. The high pressure in sturburst will naturally lead to more dense

GMCs, potentially solving with the density of SFE problems.

S. Larsen: In response to your first point: yes, it is probably true that most clusters with masses $< 10^5 M_\odot$ or so are destroyed in less than a Hubble time. So if we define "globular clusters" as clusters which can survive for a Hubble time, most of the low-mass clusters are not "globulars". At the time of formation, there may have been much larger numbers of low-mass clusters in galaxy halos, so then one can also ask whether they were "globulars" or not. I agree that we still have a lot to learn about how the properties of the ISM relate to formation of cluster. For one thing, better resolution is required to confirm the reality of SGMC's in M83 and elsewhere.

J. Holtzman: You have suggested that there is a good correlation of clusters properties with general SF rate, suggesting perhaps a universal mode of star formation. How can you accurate this with star formation in IC 10 (with few or no clusters) and perhaps the cluster age gap in the LMC?

S. Larsen: I was very interested in the IC 10 results presented by Eva Grebel. It seems puzzling that this high SFR galaxy has no massive clusters so may be there is something peculiar going on there. About the LMC, the discrepancy between the cluster and field star age distributions could perhaps be understood if the SFR was lower during the age "gap", leading to the formation of relatively low-mass clusters only. These might then not have survived to the present epoch.