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The transition between star clusters and dwarf galaxies *(Research Note)*

On the existence of a mass-radius relation for star clusters of masses $>10^7\ M_\odot$: are these objects formed in mergers of stellar systems?

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ABSTRACT

Context. At which masses does the regime of globular clusters end and the one of dwarf galaxies begin? And what separates these two classes of hot stellar systems?
Aims. We examine to what extend very massive ($>10^7\ M_\odot$) young star clusters are similar to their lower mass counter parts and to which degree they resemble other objects in their mass regime (dwarf-globular transition objects (DGTOs), ultra compact dwarf galaxies (UCDs), galaxy nuclei).
Methods. The comparison is performed by placing the recently observed very massive young clusters onto known scaling relation defined by globular clusters (with typical masses $\lesssim 10^6\ M_\odot$) and/or by hot stellar systems with sizes up to those of giant galaxies.
Results. The very massive ($\gtrsim 10^{6.5-7}\ M_\odot$) young clusters seem to show a mass-radius relation compatible with the one defined by hot stellar systems of galaxy mass. This, in turn, can explain their location on the other scaling relations investigated. It contrasts with the behaviour of the less massive young clusters and of globular clusters, which do not exhibit any mass-radius relation. However, the behaviour of the most massive globular clusters is similar to that of most other objects in that mass regime ($10^6-10^8\ M_\odot$).
Conclusions. We show that the properties of the most massive young clusters are compatible with other objects in the same mass regime such as DGTOs/UCDs. They present a possible direct avenue of formation for those objects, which does not require the transformation of a previously existing stellar system. Simulations and observations support the possibility of the formation of such very massive young clusters by early mergers of lower mass stellar clusters, which could explain the emergence of a mass-radius relation.

Key words. globular clusters: general – galaxies: dwarf

1. The transition region between massive star clusters and low-mass galaxies

In the past decade, observations have slowly filled the previous gap in the mass distribution of compact objects between globular clusters in the Milky Way ($\lesssim 10^6\ M_\odot$) and compact low-mass galaxies such as M 32 (several $10^8\ M_\odot$). This has triggered many questions about the nature of such objects, which lie in the mass range 10^6 to $10^8\ M_\odot$.

Attention was first drawn to these objects by the discovery of very massive ($\gtrsim 10^6\ M_\odot$), compact stellar systems in Fornax (Minniti et al. 1998; Hilker et al. 1999a,b; Drinkwater et al. 2000), later baptised "Ultra Compact Dwarf" (UCD) galaxies. The origin of these objects is still hotly debated in the literature: they have been proposed to be the high mass end of the globular cluster population, the nuclei of stripped galaxies, merged star clusters ("stellar superclusters") or a new class of compact dwarf galaxies (Hilker et al. 1999a,b; Drinkwater et al. 2000; Phillipps et al. 2001; Fellhauer & Kroupa 2002; Bekki et al. 2003, 2004; Drinkwater et al. 2003; Maraston et al. 2004; Mieske et al. 2004; Haşegan et al. 2005). Haşegan et al. (2005) introduced the term "Dwarf-Globular Transition Objects" (DGTOs) in order to emphasize the ambiguity of their classification.

The fundamental open question is the formation process of these objects. To answer this question, their location on various scaling relations has been investigated and compared to the loci of other known objects in that mass regime (such as massive globular clusters, nuclei of dwarf galaxies, nuclear clusters in bulge-less spirals, simulated merged clusters; see above references and Walcher et al. 2005).

Young massive clusters were first placed on σ against M_V scaling relation in Kissler-Patig (2004) and in the κ-plane in Maraston et al. (2004), and it was noticed that the most massive cluster departed from the globular cluster relation in the direction of UCDs (see also de Grijs et al. 2005, for an extensive discussion). However, as discussed also in Bastian et al. (2006a), such relations are problematic as they require a correction of the absolute magnitude M_V for evolution (prone to errors in the distance, the age and the evolutionary model) which complicates the analysis.

Haşegan et al. (2005) suspect a break in the scaling relations of star clusters and galaxies around 10^6 $M_\odot$. The authors suggest that above that mass, DGTOs/UCDs appear to split in two groups. Some DGTOs/UCDs follow an extrapolation of the globular cluster scaling relations to high masses: they are considered to be globular clusters with unusually high mass and luminosity. Others fall along the galaxy scaling relations: they are viewed as prime UCD candidates.

Geha et al. (2002) put dE,N nuclei on scaling relations and find them to fall in the range spanned by globular clusters, although slightly offset in mass. No direct comparison with DGTOs/UCDs was made.

Walcher et al. (2005) notice that nuclear clusters (thought to grow by continuous mass accretion), when put on scaling relations, are in general more compact then UCDs.

Fellhauer & Kroupa (2002) and Bekki et al. (2004) argue that the properties of the simulated product of multiple merging of star clusters reproduces well the properties of UCDs/DGTOs.

In this contribution, we add a piece to the puzzle by placing recently observed *young massive star clusters* with masses $\gtrsim 10^7$ $M_\odot$ on the various scaling relations. This allows us to shed new light on the origin of the objects in this regime. It also shows that objects with the properties of UCDs/DGTOs can be formed directly as a consequence of star cluster formation. Thus, their formation does not seem to necessarily require the transformation of a parent stellar system such as a dwarf galaxy.

2. Young star clusters with mass of 10^6 $M_\odot$ and above

We are searching for counter-parts of UCDs/DGTOs, i.e. compact objects with masses $>10^6$ $M_\odot$ (ideally $>10^7$ $M_\odot$) *of known origin*. Massive star/globular clusters are the first objects that come to mind, but star clusters with masses $>10^7$ $M_\odot$ are not known in the Local Group. Moreover, old objects (e.g. as ω Centauri) have a nature/origin that is still under debate (e.g. Hilker et al. 2004, and reference therein).

However, some *young* massive star clusters found in major star forming regions (typically galaxy collisions) are known to have (photometrically determined) masses in the regime of interest. The advantage of young objects is that they do not have much of a past. Their properties reflect their short period of formation. Their age is known, so that even if they are made up by merging fragments or clusters, all of them formed in the same starburst. Furthermore, young massive clusters (as opposed to e.g. a nucleus of a dwarf galaxy stripped of its envelope) are not expected to have any significant dark matter.

Recently, a handful of such system have had their masses determined *dynamically* (Maraston et al. 2004; Bastian et al. 2006a). They are prime candidates to be compared with UCDs. Maraston et al. (2004) did so for the most massive of them (NGC 7252:W3), and came to the conclusion that it has remarkably similar properties to the mysterious UCDs. The case which was made for one object may have failed to make a general point, but is reinforced below with the addition of new objects from Bastian et al. (2006a).

3. Young massive star clusters on the scaling relations of low-mass, hot stellar systems

3.1. Placing the young massive star clusters on the scaling relations

Scaling relations are recognized as prime tools to understand the evolution of hot stellar systems (e.g., Djorgovski & Davis 1987; McLaughlin 2000). Given that we aim to compare young systems with old ones, we chose to avoid any relation that involves the Mass-to-Light ratio. Although we think that the "aging" of the young star clusters is well understood, we prefer not to add this uncertainty to our analysis. We note that Maraston et al. (2004) and Bastian et al. (2006a) show convincingly that the systems will evolve into stellar populations with "normal" M/L ratios similar to DGTOs/UCDs, i.e. between 2 and 6, as expected for old metal-rich systems not significantly dominated by dark matter.

Thus, we exclude the Faber-Jackson relation (Faber & Jackson 1976) as well as the κ-space (Bender et al. 1992; Burstein et al. 1997) to focus on relations between mass and, in turn, velocity dispersion, half-light radius, and mean mass density within the half-light radius (see Haşegan et al. 2005, for a detailed discussion of these relations).

In order to compare the young clusters with the old objects on these relations, we need to estimate their evolution in the above quantities. Literature on the dynamics of star clusters and their evolution is extensive and spans the last century. We mention here only some of the most recent N-body simulations that focus on star clusters with high masses (Fellhauer & Kroupa 2005; Baumgardt et al. 2004). The simulations agree on the fact that after the first few 10^6 years, massive clusters evolve only slowly in mass, velocity dispersion and radius. For example, Fellhauer & Kroupa (2005; see also Fellhauer & Kroupa 2002) specifically tried to reproduce the cluster NGC 7252:W3. After ~300 Myr (a lower limit for the cluster age), the velocity dispersion decreases by 10−20% over the next several Gyr, while the mass drops by ~30%, and the effective radius reacts by rising to ~10 pc. Note that the relatively small simulated effective radius is at odds with the observations. Fellhauer & Kroupa argue the observed larger radius could be explained if NGC 7252:W3 was seen at a the time of a late merging event. The clusters NGC 7252:W30 ($R_{\rm eff}$ ~ 9 pc)

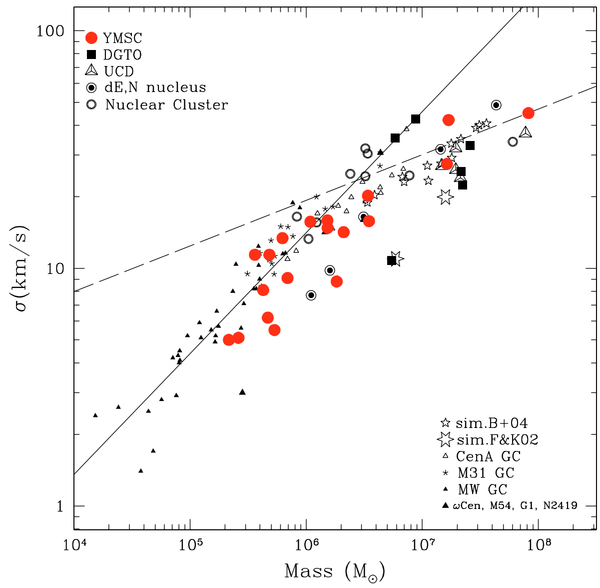

Fig. 1. Scaling relations for low-mass, hot stellar systems: line-of-sight velocity dispersion plotted against total mass. For details on the objects plotted, see text. The solid and dashed lines show the fitted relations for globular clusters and elliptical galaxies, respectively.

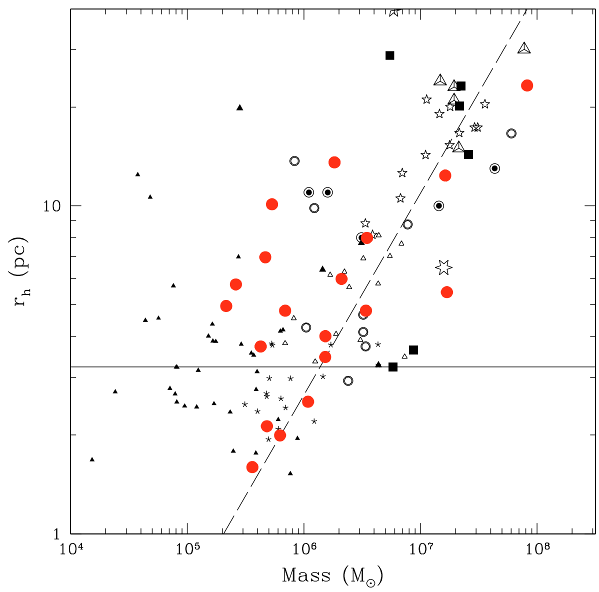

Fig. 2. Scaling relations for low-mass, hot stellar systems: half-light radius plotted against total mass. For details on the objects plotted, see text (symbols as in Fig. 1). The dashed line shows the fitted relation for elliptical galaxies, while the solid lines indicates the median for Galactic globular clusters (r_h = 3.2 pc) that do not follow a mass-radius relation.

and NGC 1316:G114 ($R_{\rm eff}$ ~ 4 pc) are better matched by the simulations.

The cluster of most interest in our context are the most massive known (NGC 7252:W3, NGC 7252:W30, NGC 1316:G114). They have ages between 500 Myr and 3 Gyr and their mass, radius and velocity dispersion are thus likely to evolve by modest factors as discussed above. We do not attempt to correct for evolution in our comparison but keep this uncertainty in mind when reaching conclusions.

We used the young star-cluster data as tabulated in Maraston et al. (2004) and Bastian et al. (2006a, including the literature collection of their Table 5 for less massive young star clusters). The projected effective radius ($R_{\rm eff}$) was transformed into an unprojected half-light radius (r_h) according to $r_h = 1.3\ R_{\rm eff}$ (Spitzer 1987). The mass (M) was computed according to $M = \eta\sigma^2 r_h/G$, where σ is the line-of-sight velocity dispersion, G the gravitational constant, and $\eta = 7.5$ (see Boily et al. 2005, and references therein for discussions on η)[1]. The mean mass density within the half-light radius, $\langle\Sigma_h\rangle$, is derived from the two above quantities (as $\langle\Sigma_h\rangle = 0.5M/(\pi R_{\rm eff}^2)$).

The data for young massive star clusters (*solid circles*) are plotted on three scaling relations in Figs. 1–3, together with the data for other low-mass, hot stellar systems. Specifically, we show globular clusters belonging to the Milky Way, M 31 (McLaughlin & van der Marel 2005), and NGC 5128 (Martini & Ho 2004; Harris et al. 2002), nuclei of dE,N (Geha et al. 2002), UCDs (Drinkwater et al. 2003), DGTOs (Haşegan et al. 2005), nuclear clusters (Walcher et al. 2005), as well as simulation of multiple merged star clusters (Fellhauer & Kroupa 2002, 2005; Bekki et al. 2004, for the latter only selected data points that cover the range of properties span by the simulations). We also plot the fitted scaling relations for

[1] With σ in km s^{-1} and r_h in pc, this results in $M/M_\odot = 1744 \cdot \sigma^2 r_h$.

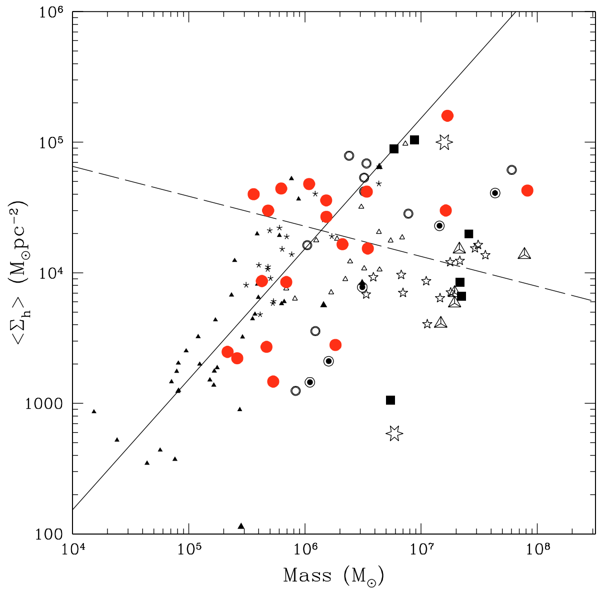

Fig. 3. Scaling relations for low-mass, hot stellar systems: mean mass density within the half-light radius plotted against total mass. For details on the objects plotted, see text (symbols as in Fig. 1). The solid and dashed lines show the fitted relations for globular clusters and elliptical galaxies, respectively.

globular clusters (*solid line*) and elliptical galaxies (*dashed line*) as derived in Haşegan et al. (2005).

Note that the three scaling relations are not independent as they plot, in the above order, σ^2 against $\sigma^2 r_h$, r_h against $\sigma^2 r_h$ and σ^2/r_h against $\sigma^2 r_h$. Yet, they exhibit different enough views on these quantities that they are worth being considered individually.

3.2. Young massive star clusters: where do they fit?

We review below where the young massive star clusters fall on the three scaling relations.

In Fig. 1, the young massive star clusters follow nicely the relation spanned by the globular cluster for masses $<10^6$ $M_\odot$ to then continue at higher masses along the sequence defined by elliptical galaxies. Thus, while the lower-mass star clusters are indistinguishable from globular clusters, the higher-mass ones consolidate a sequence on which also the most massive DGTOs, nuclear clusters, UCDs, dE,N nuclei fall. The σ-mass relation "bends over" for masses greater than $\sim 3 \times 10^6$ $M_\odot$. This can be understood as a consequence of the mass-radius relation (see below) that appears to hold for objects above this mass: more massive clusters will be less dense, which in turn will lead to a lower velocity dispersion. The most massive young star clusters are indistinguishable in this relation from UCDs/DGTOs, dE,N nuclei and nuclear clusters.

Figure 2 shows a relation between radius and total mass for the young massive star clusters. They fall on the relation defined by elliptical galaxies, on which also DGTOs/UCDs, dE,N nuclei and nuclear clusters lie. Such a relation is not observed for globular clusters (McLaughlin 2000; Jordán et al. 2005), nor for young massive clusters with masses below 10^5 $M_\odot$ (Zepf et al. 1999; Larsen 2004; Bastian et al. 2005a). Other trends are apparent, e.g. the young massive star clusters with $<10^6$ $M_\odot$ might be systematically slightly larger at a given mass then defined by the overall relation. Uncertainties in the mass and radius determination make any firm statements difficult, though.

The third scaling relation (Fig. 3) exhibits a similar results as Fig. 1 (as it essentially shows $\sigma^2/r_{\rm h}$ against $\sigma^2 r_{\rm h}$ instead of σ^2 against $\sigma^2 r_{\rm h}$). Interestingly, the most massive, young star clusters range among the objects with the highest mass densities at a given mass. NGC 1316:G114 even exhibits the highest mass density inside a half-light radius ever observed among low-mass hot stellar systems ($\langle\Sigma_{\rm h}\rangle > 10^5$ $M_\odot$ pc^{-2}). The large scatter prevents from defining a clear trend, but again the young massive star cluster appear to "bend over" and to follow a shallower relation than the one defined by globular clusters.

In all three relations, the simulated products of multiple merging of star clusters (Bekki et al. 2004; Fellhauer & Kroupa 2005) reproduce very well the most massive, young star clusters. The Fellhauer & Kroupa (2005) simulations produce quite compact star clusters, and thus are unable to fit NGC 7252:W3 and NGC 7252:W30, but match well the observed properties of NGC 1316:G114, which the simulations of Bekki et al. (2004) fail to reproduce well.

We note, finally, that the (seven) young massive clusters lying well *below* the mass-surface density relation of *galaxies* (see Fig. 3, $\langle\Sigma_{\rm h}\rangle < 10^4$ $M_\odot$ pc^{-2}), are also the ones that lie the furthest below the mass-σ relation of galaxies, and the ones to the far left of the mass-radius relation.

4. Discussion and conclusions

The newest mass measurements of young clusters with masses greater than 10^7 $M_\odot$ show that these objects overlap in the scaling relations with DGTOs/UCDs and other objects in that mass regime. In particular, the most massive young clusters seem to follow the same mass-radius relation as DGTOs/UCDs and elliptical galaxies. *This suggests that DGTOs/UCDs are compatible with having the same nature/origin as the most massive young clusters.* An open question is the ability for the evolved products of these massive young clusters to reproduce the high mass-to-light ratios observed for DGTOs (Haşegan et al. 2005).

We can then ask: what is the formation process for these most massive young clusters? As mentioned already above, independent simulations (Bekki et al. 2004; Fellhauer & Kroupa 2005), as well as recent observations (Larsen et al. 2002; Minniti et al. 2004; Bastian et al. 2006b) point towards the idea that these objects could be products of early star cluster mergers, occurring in the first tens to hundred Myr. Our results are consistent with this hypothesis.

Note that *late* mergers of star/globular clusters are not excluded as an alternative formation process for very massive star clusters. Oh & Lin's (2000) simulations show that old star clusters can, through orbital decay, sink into the center of a dwarf galaxy and assemble to form a very massive star cluster. While it could potentially apply to (some?) DGTOs/UCDs, it cannot explain *young* massive clusters such as discussed here.

Are the most massive young clusters a distinct class of objects with respect to globular or lower mass young clusters? At face value, the scaling relations appear to differ. In particular, globular clusters and young massive clusters with masses of less than 10^5 $M_\odot$ do not appear to follow a mass-radius relation (which in turn, when combined with the virial theorem, would explain why the σ-mass and $\langle\Sigma_{\rm h}\rangle$-mass relations "bend over"). The study of star cluster complexes and their associated giant molecular clouds (Bastian et al. 2005b) showed that the emergence of a mass-radius relation seems to occur at scales between individual star clusters and cluster complexes. The complexes show a similar relation as their parent giant molecular clouds. This would strengthen the assumption that the most massive star clusters, and potentially some DGTOs/UCDs, are associated with star cluster complexes, i.e. star cluster merger events.

As an alternative to the above scenario, one could speculate that all star clusters form with a primordial mass-radius relation, but only the most massive star clusters are able to retain it against processes that would erase it (cf. Ashman & Zepf 2001; Bastian et al. 2005a. But given the lack of theoretical and observational support for this scenario, we currently favor the first hypothesis: objects in the mass range $10^6 \leq M \leq 10^8$ $M_\odot$ are likely to be the lowest mass structures resulting from merger of stellar systems, with the merging process being at the origin of a mass-radius relation. If the most massive star clusters indeed form by mergers and the typical globular clusters not, the two populations must overlap in some mass regime (10^5–10^6 $M_\odot$?). The caveat is that the scenario cannot answer the question why globular clusters do not show a mass-radius relation, in contrast to the molecular clouds in which they are thought to be formed. But this scenario, in which young massive star clusters are the product of star cluster merger events, would explain their presence at the lowest mass end of the galaxy scaling relations extending from the dwarf galaxy regime to giant ellipticals.

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Note added in proof. Alister Graham kindly pointed out that the dashed line in Fig. 3 shows the relation for giant ellipticals, whereas dwarf galaxies follow a trend having the opposite slope, i.e. closer to the relation for globular clusters.

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