Star clusters: basic galactic building blocks
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Nuclear star clusters

Torsten Böker

European Space Agency, Keplerlaan 1, 200AG Noordwijk, the Netherlands
email: tboeker@rssd.esa.int

Abstract. The centers of most galaxies in the local Universe are occupied by compact, barely resolved sources. Based on their structural properties, position in the Fundamental Plane, and integrated spectra, these sources clearly have a stellar origin. They are therefore called 'nuclear star clusters' (NCs) or 'stellar nuclei'. NCs are found in galaxies of all Hubble types, suggesting that their formation is intricately linked to galaxy evolution. Here, I review some recent studies of NCs, describe ideas for their formation and subsequent growth, and touch on their possible evolutionary connection with both supermassive black holes and globular clusters.

Keywords. galaxies: nuclei, galaxies: star clusters

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1. Introduction

The nuclei of galaxies are bound to provide 'special' physical conditions because they are located at the bottom of the potential well of their host galaxies. This unique location manifests itself in various distinctive phenomena such as supermassive black holes (SMBHs), active galactic nuclei (AGN), central starbursts, or extreme stellar densities. The evolution of galactic nuclei is closely linked to that of their host galaxies, as inferred from a number of global-to-nucleus scaling relations discovered in the last decade.

Recently, observational and theoretical interest has been refocussed onto the compact and massive star clusters found in the nuclei of galaxies of all Hubble types. These 'nuclear star clusters' (NCs) are intriguing objects that are linked to a number of research areas: (i) they are a promising environment for the formation of massive black holes because of their extreme stellar densities, (ii) they may also constitute the progenitors of at least some halo globular clusters through 'NC capture' following the tidal disruption of a satellite galaxy, and (iii) their formation process is influenced by (and important for) the central potential, which in turn governs the secular evolution of their host galaxies.

I will briefly summarize what has been learned about NCs over the last few years, describe some proposed formation mechanisms of NCs, and discuss the new paradigm of 'central massive objects', which links NCs with SMBHs in galactic nuclei. Finally, I briefly mention a scenario in which NCs may be the progenitors of (some) globular clusters.

2. Properties of nuclear star clusters

Extragalactic star clusters are compact sources, and in general their study requires high spatial resolution, afforded only by the *Hubble Space Telescope* or large ground-based telescopes using adaptive optics. Over the last decade, a number of studies—based on both imaging and spectroscopic observations—have contributed to the following picture of NCs:

(*a*) NCs are common: the fraction of galaxies with an unambiguous NC detection is 75% in late-type (Scd–Sm) spirals (Böker *et al.* 2002), 50% in earlier-type (Sa–Sc) spirals (Carollo *et al.* 1997), and 70% in spheroidal (E and S0) galaxies (Côté *et al.* 2006). These

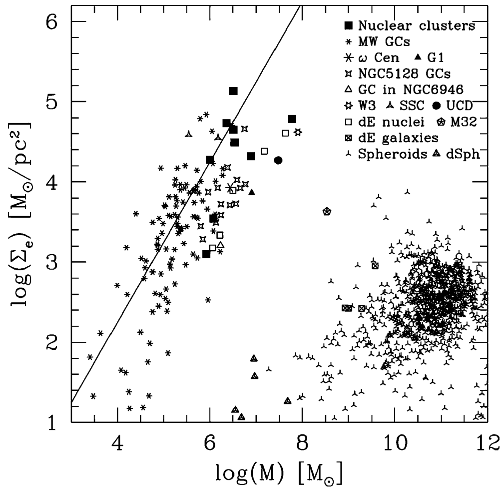

Figure 1. Mean projected mass density of various stellar systems inside the effective radius, r_e, plotted against total mass. This is similar to a face-on view of the Fundamental Plane. NCs occupy the high end, a region populated by other types of massive stellar clusters, and are well separated from elliptical galaxies and spiral bulges. The solid line represents a constant cluster size, i.e., $r_e = 3$ pc (from Walcher *et al.* 2005).

numbers are likely lower limits, although for different reasons. In the latest-type disks, it is sometimes not trivial to locate the galaxy center unambiguously so that no particular source can be identified with it. In contrast, many early-type galaxies have very steep surface brightness profiles (SBPs) that make it difficult to detect even luminous clusters against this bright background.

(*b*) NCs are much more luminous than 'normal' globular clusters (GCs). With typical absolute *I*-band magnitudes between −14 and −10 (Böker *et al.* 2002; Côté *et al.* 2006), they are roughly 40 times more luminous than the average Milky Way globular cluster (Harris 1996).

(*c*) However, NCs are as compact as Milky Way GCs. Their half-light radii are typically 2 − 5 pc, independent of galaxy type (Geha *et al.* 2002; Böker *et al.* 2004; Côté *et al.* 2006).

(*d*) Despite their compactness, NCs are very massive: their typical dynamical mass are $10^6 - 10^7$ $M_\odot$ (Walcher *et al.* 2005), i.e., at the extreme high end of the globular cluster mass function.

(*e*) Their mass density clearly separates NCs from compact galaxy bulges. This is demonstrated in Figure 1, which compares the mass and mass density of NCs to those of other spheroidal stellar systems. The clear gap between bulges/ellipticals on the one hand, and NCs on the other makes a direct evolutionary connection between the two classes of objects unlikely.

(*f*) The star-formation history of NCs is complex, as evidenced by the fact that most NCs have stellar populations composed of multiple generations of stars (Walcher *et al.* 2005; Rossa *et al.* 2006). While all NCs show evidence for an underlying old ($\gtrsim$ 1 Gyr) population of stars, most also have a young generation with ages below 100 Myr. This is strong evidence that NCs experience frequent and repetitive star-formation episodes (Walcher *et al.* 2005).

(*g*) NCs obey similar scaling relations with host-galaxy properties as SMBHs. This has triggered a very active research area, but its implications are still to be understood fully, as discussed in more detail in Section 4.

3. Possible formation mechanisms

There are a number of suggested formation scenarios for NCs, and so far few have been ruled out. In principle, one can distinguish between two main categories: (i) migratory formation scenarios in which dense clusters form elsewhere in the galaxy and then fall into the center through dynamical friction or other mechanisms (Andersen *et al.* 2008; Cappuzzo–Dolcetta & Miocchi 2008), and (ii) in situ cluster buildup through (possibly episodic) gas infall and subsequent star formation within a few parsecs from the galaxy center.

The processes that funnel gas onto NCs in nearby galaxies have recently been studied in some detail, enabled by significant improvements in the sensitivity and spatial resolution of millimeter-wave interferometers (e.g., Schinnerer *et al.* 2006, 2007). In general, bar-shaped asymmetries in the disk potential can lead to a prolonged influx of molecular gas into the central few pc, thus providing the reservoir for an intense burst of star formation and leading to the rejuvenation of an existing NC. The starburst is, however, self-regulating in the sense that mechanical feedback from stellar winds and/or supernova explosions can expel the remaining gas and even temporarily change the gas-flow pattern (Schinnerer *et al.* 2008). This scenario naturally leads to episodic star formation, thus explaining the presence of multiple stellar populations in NCs.

Less clear, however, are the reasons as to why gas accumulates in the nucleus of a shallow disk galaxy *in the absence* of a prominent central mass concentration, i.e., how the 'seed clusters' form initially. A few studies have attempted to provide an explanation for this puzzle. For example, Milosavlević (2004) suggests the magneto-rotational instability in a differentially rotating gas disk as a viable means to transport gas towards the nucleus and support (semi-)continuous star formation there.

More recently, Emsellem & van de Ven (2008) pointed out that the tidal field becomes compressive in shallow density profiles, causing gas to collapse onto the nucleus of a disk galaxy. If correct, then NC formation is indeed expected to be a natural consequence of galaxy formation, which would go a long way towards explaining at least some of the observed scaling relations between NCs and their host galaxies.

The question of when a particular NC (i.e., its 'seed' cluster) has formed is equivalent to asking how old its oldest stars are. This question is extremely difficult to answer in all galaxy types, albeit for different reasons. In late-type spirals, for example, the NC nearly always contains a young stellar population which dominates the spectrum and thus makes detection of an underlying older population challenging, not to mention its accurate age determination.

Early-type galaxies, on the other hand, have much steeper surface brightness profiles and, therefore, a low contrast between the NC and the galaxy body. This makes spectroscopic studies of NCs in ellipticals and S0s exceedingly difficult. The few published studies have focused on the NCs of dE,N galaxies and showed that even these can have stellar populations that are significantly younger than the rest of the host galaxy (Butler & Martínez–Delgado 2005; Chilingarian *et al.* 2007; Koleva *et al.* 2009). In general, stellar population fits as well as the rather high dynamical mass-to-light ratios of NCs indicate that they contain a significant population of evolved (at least 1 Gyr old) stars, i.e., they have been in place for a long time (Walcher *et al.* 2005).

4. Central black holes and nuclear star clusters

A number of recent studies (Rossa *et al.* 2006; Wehner & Harris 2006; Ferrarese *et al.* 2006; Balcells *et al.* 2007; Graham & Driver 2007) have demonstrated that NCs follow similar scaling relations with their host galaxies as SMBHs and typically extend these

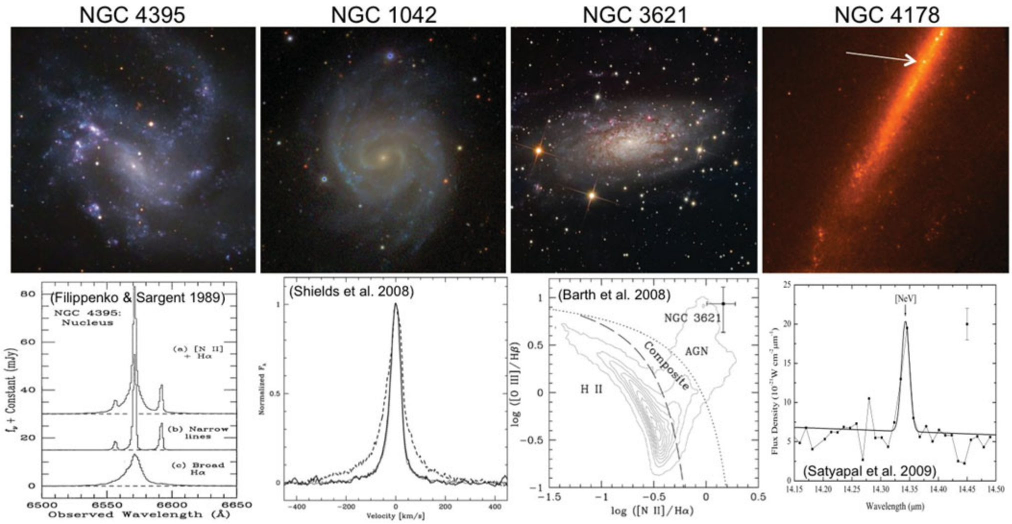

Figure 2. Four bulgeless disk galaxies with evidence for an active galactic nucleus (AGN; references in the lower panels). The case of NGC 4395 has long been thought unique, but detailed observations of other late-type disks have shown that such low-luminosity AGN are easily missed in optical surveys. Nevertheless, the AGN fraction in bulgeless disks appears to be lower than in galaxies with more massive bulges.

relations to lower SMBH masses. This has triggered speculation about a common formation mechanism of NCs and SMBHs, which is governed mostly by the mass of the host galaxy's spheroid. The idea put forward is that NCs and SMBHs are two incarnations of a 'central massive object' (CMO). Galaxies above a certain mass threshold ($\approx 10^{10}$ $M_\odot$) form predominantly SMBHs while lower-mass galaxies form NCs.

On the other hand, it is well established that many galaxies contain *both* a NC and a SMBH (Seth *et al.* 2008). This is true even at the extreme late end of the Hubble sequence, i.e., in galaxies that have no bulge component at all. A famous example known for a long time is the 'mini Seyfert' NGC 4395 (Filippenko & Sargent 1989), but a number of similar cases have been found recently, as demonstrated in Figure 2. These active galactic nuclei (AGN) are often missed in spectra taken with relatively wide apertures because the AGN signatures are faint compared to those of their surroundings, especially in the presence of (circum)nuclear star formation.

However, this does not imply that *all* NCs harbor a SMBH. On the contrary, a recent survey of high-ionization [NeV] emission in late-type galaxies (Satyapal *et al.* 2009) indicates that AGN in bulgeless disks are indeed rare: only about 5% of spirals with Hubble type Sd–Sm show [NeV] emission. Interestingly, all these low-luminosity 'mini AGN' are found in galaxies that also host an NC, possibly suggesting that the presence of an NC is necessary (but not sufficient) for the formation of a SMBH.

Why, then, do some NCs contain a SMBH, but not all? What is the mass ratio between NCs and SMBHs and how is it regulated? Important observational constraints come from Graham & Spitler (2009), who identified all galaxies with reliable measurements of both NC mass and SMBH mass. They conclude that the ratio $M_{\rm BH}/(M_{\rm BH}+M_{\rm NC})$ is a function of bulge mass, as illustrated in Figure 3. Massive bulges only host SMBHs, but no NCs. At the other end of the spectrum, in 'pure' disk galaxies, the mass of the SMBH (if it exists at all) is negligible with respect to the NC mass. In between, there is a transition region in which galaxies host both NCs and SMBHs with comparable masses.

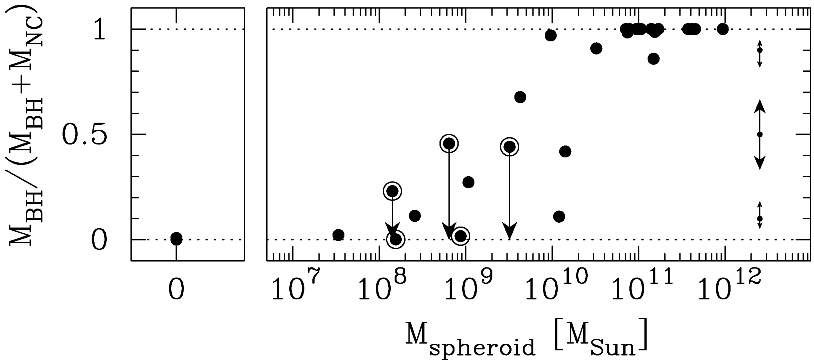

Figure 3. The increasing dominance of the central BH over the NC of stars, traced by the mass ratio $M_{\rm BH}/(M_{\rm BH} + M_{\rm NC})$ appears to depend on the bulge mass $M_{\rm sph}$ of the host galaxy. The leftmost data point indicates globular clusters, which have zero bulge mass. In contrast, the highest-mass spheroids with the most massive BHs do not contain a NC (from Graham & Spitler 2009).

A theoretical explanation as to why this may be so has been offered by Nayakshin *et al.* (2009). They speculate that 'competitive feedback' between the SMBH and the gas inflow feeding star formation during the NC's buildup determines which of the two components can grow more efficiently. The outcome of this 'race' between the SMBH (which grows on the Salpeter timescale) and the NC (which should grow on the dynamical timescale regulating gas inflow) is decided by the bulge mass, i.e., the stellar velocity dispersion, σ. Below a value of $\sigma \approx 150$ km s^{-1}, the BH cannot grow efficiently, while above this value it grows fast enough that its radiative feedback hinders NC growth. The presence of a SMBH also has important consequences for the dynamical evolution of an NC, since it prevents core collapse and might even disrupt the NC (Merritt 2009).

One important question in this context, which has been neglected so far, is why some galaxies apparently contain *neither* NC nor SMBH. In other words, how can a galaxy avoid having a CMO? Progress along these lines will require a better understanding of the formation and survival of 'pure' disk galaxies, a problem that is still challenging for current models of structure formation.

5. Nuclear clusters as precursors of globular clusters

As mentioned in Section 3, most NCs likely formed a long time ago. In fact, some theories of structure formation suggest that already the first protogalaxies underwent rapid nucleation (Cen 2001) and formed a dense star cluster in their center. If these protogalaxies are gas rich, the NC will most likely experience multiple bursts of star formation similar to the present-day NCs in late-type disks. This process continues until the protogalaxy is destroyed in a merger. Because of its compactness and high stellar density, the NC will survive the merger and from that moment on will passively age in the halo of the merger product.

That this process indeed occurs is best demonstrated by the case of M 54. This Milky Way globular cluster is believed to be the nucleus of the Sagittarius dwarf galaxy (Layden & Sarajedini 2000) which is currently being 'swallowed' by the Milky Way. Another plausible example is ω Cen which has long been thought to be the remnant nucleus of an accreted dwarf galaxy because of it extreme mass and multiple stellar populations.

Assuming that globular clusters spent some part of their history at the bottom of a galaxy's potential well might naturally explain the multiple stellar populations observed in a number of globulars in the Galaxy (Böker 2008). It is also consistent with the roughly constant specific frequency of globular clusters and the observed universal mass fraction of globular cluster systems in the local Universe (McLaughlin 1999).

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