Properties of nuclear star clusters

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Abstract. Over the last decade, HST imaging studies have revealed that the centers of most galaxies are occupied by massive, yet compact, stellar clusters. These “nuclear star clusters” (NSCs) are found in a wide range of Hubble types, suggesting that their formation is intricately linked to galaxy evolution. In this review, I briefly summarize what has been learned about NSCs, mention some ideas for their formation, and touch on more speculative links between NSCs, super-massive black holes, and globular clusters.

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 active galactic nuclei (AGN), central starbursts, or extreme stellar densities. Moreover, 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.

For these reasons, observational and theoretical interest has recently refocused onto the compact, but clearly resolved sources that are found in the nuclei of many nearby galaxies. Especially in images of low-surface brightness galaxies, these objects stand out clearly. They are easily recognized in surface brightness profiles because they are responsible for a pronounced upturn above the inward extrapolation of the disk/bulge profile (see Figure 1). As the surface brightness of the underlying galaxy increases, the contrast between NSC and disk and/or bulge decreases, and NSC detection becomes increasingly difficult. [9] have pointed out that in early-type galaxies, the amount of central light excess attributable to an NSC appears to form a monotonous function of galaxy luminosity: while fainter galaxies often show a pronounced light excess, there even is a light deficit in galaxies at the bright end of the luminosity function, in the sense that at small radii, their surface brightness falls below the inward extrapolation of the galaxy profile.

Based on their structural properties, position in the fundamental plane, and spectra, these compact sources clearly have a stellar origin. They are therefore called “stellar nuclei” or “nuclear star clusters” (NSCs). Historically, the nuclei of dE,N galaxies have been best studied, but it has become clear recently that similar objects exist also in normal spirals and ellipticals. At face value, NSCs are an intriguing environment for the formation of massive black holes because of their extreme stellar density. NSCs may also constitute the progenitors of at least some halo globular clusters via “NSC capture” following the tidal disruption of a satellite galaxy, a scenario that is explored further in § 4. Finally, their formation process is influenced by (and important
Figure 1. Top: HST/WFPC2 F814W (I-band) images of three representative nuclear star clusters. Shown is the PC chip with a field of view of $\approx 35'' \times 35''$. The bar in the top left of each panel denotes a spatial scale of 1 kpc, the north-east orientation is indicated by the compass arrow. Bottom: I-band surface brightness profiles, measured from elliptical isophote fits to the images above. Note the clear transition between the underlying disk and the NS at radii around $0.2''$. Also shown are analytical fits to the disk and cluster profiles that yield the cluster photometry (for details, see [1]).

for) the central potential, which in turn governs the secular evolution of their host galaxies. In what follows, I briefly summarize what has been learned about NSCs over the last few years.

2. Properties of Nuclear Star Clusters
Extragalactic star clusters are compact sources, and in general, their study requires space-based resolution. It does not come as a surprise, therefore, that the Hubble Space Telescope (HST) has been instrumental for recent progress in the understanding of NSCs. Over the last decade, a number of HST studies - both via imaging and spectroscopic observations - have contributed to the following picture of NSCs:

- NSCs are common: the fraction of galaxies with an unambiguous NSC detection is 75% in late-type (Sd-I) spirals [1], 50% in earlier-type (Sa-Sc) spirals [6], and 70% in spheroidal (E & S0) galaxies [8]. All these 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.
- NSCs are much more luminous than “normal” globular clusters (GCs). With typical absolute I-band magnitudes between -14 and -10 [1, 8], they are roughly 40 times more
Figure 2. Mean projected mass density of various stellar systems inside their effective radius $r_e$, plotted against their total mass. This is similar to a face-on view of the fundamental plane. NSs occupy the high end of 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 [25]).

- However, NSs are as compact as Galactic GCs. Their half-light radius typically is $2 - 5$ pc, independent of galaxy type [2, 13, 8].
- Despite their compactness, NSs are very massive: their typical dynamical mass is $10^6 - 10^7 M_\odot$ [25] which is at the extreme high end of the GC mass function.
- Their mass density clearly separates NSs from compact galaxy bulges. This is shown in Figure 2 which compares the mass and mass density of NSs to that of other spheroidal stellar systems. The clear gap between bulges/ellipticals on the one hand, and NSs on the other hand makes a direct evolutionary connection between the two classes of objects unlikely.
- The star formation history of NSs is complex, as evidenced by the fact that most NSs have stellar populations comprised of multiple generations of stars [26, 19]. The youngest generation is often younger than 100 Myr which is strong evidence that NSs experience frequent and repetitive star formation episodes [26].
- Due to three recent and independent studies of NSs in different galaxy types [19, 27, 8], it has become clear that NSs obey similar scaling relationships with host galaxy properties as do supermassive black holes. As an example, Figure 3 shows the NS mass as a function of bulge luminosity. While the implications of this result are not yet clear (see § 5), these studies have renewed interest in NSs because of the potentially important role that NSs play in the evolution of their host galaxies.

3. How (and when) do Nuclear Clusters Form?

There are a large number of suggested formation scenarios for NSs, and so far, few have been ruled out. In principle, one can distinguish between two main categories: a) migratory formation scenarios in which dense clusters form elsewhere in the galaxy, and then fall into the center via
Figure 3. Relation between NSC mass in spiral galaxies and bulge luminosity log($L_B / L_\odot$) of the host galaxy (from [19]). Open symbols denote early-type spirals, and filled symbols denote late-type spirals. There is a strong correlation in the sense that galaxies with more luminous bulges have more massive NSCs. The solid line indicates the best linear fit to the data, while the dashed line indicates the relation between black hole mass and bulge luminosity for the sample of [15].

dynamical friction or other mechanisms, and b) in-situ cluster build-up via (possibly episodic) gas infall and subsequent star formation within a few parsecs from the galaxy center.

Simulations of the orbital decay and subsequent merging of globular clusters have been investigated by [5] who conclude that this is indeed a viable formation scenario, at least under certain starting conditions. Analytical calculations presented in [18] confirm that the expected amount of mass contributed by infalling star clusters over a Hubble time is consistent with the typical NSC masses observed today.

On the other hand, we now know that infall of molecular gas into the central few pc does occur. Molecular gas is the raw material for star formation, and thus is likely to affect the NSC evolution. Progress in this field has been enabled by significant improvements to the sensitivity and spatial resolution of mm-interferometers. As an example, Figure 4 shows the distribution of CO in the nearby spiral NGC 6946. Both the morphology and the kinematics of the gas can be well explained by the effects of a small-scale stellar bar. The S-shaped flow pattern onto the nucleus and the large ($1.6 \cdot 10^7 M_\odot$) gas concentration in the inner $\approx 10$ pc lend credibility to the “repetitive burst” scenario for NSC growth.

Less clear, however, are the reasons for 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, [17] suggests the magneto-rotational instability in a differentially rotating gas disk as a viable means to transport gas towards the nucleus and to support (semi)continuous star formation there. More recently, [10] have 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 NSC 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 NSCs and their host galaxies.

The question of when a particular NSC (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 NSC nearly always
contains a young stellar population which dominates the spectrum and thus makes the detection of an underlying older population challenging, not to mention its accurate age determination.

Early-type, spheroidal galaxies, on the other hand, lack the large gas reservoirs of spirals, and thus should experience less frequent nuclear starbursts. One therefore would expect their NSCs to contain fewer and older stellar populations. However, early-type galaxies have much steeper surface brightness profiles, and therefore a low contrast between NSC and galaxy body. This makes spectroscopic studies of NSCs in E’s and S0’s exceedingly difficult. The few published studies have focused on the NSCs of dE,N galaxies, and have shown that even these can have rather young (few hundred Myrs) stars, as demonstrated e.g. by [4] in the case of NGC 205. Generally speaking, however, most NSCs in dE,N galaxies have integrated colors that - while different from those of their host galaxies - are generally consistent with evolved stellar populations at least 1 Gyr old [24]. Considering that there may be even older stellar populations “hiding”, this age likely constitutes only a lower limit for the oldest stellar population in dE,N nuclei.

In fact, it is not implausible that the “seed clusters” for present-day NSCs were in place very early in the universe. The average star formation rate over the last 100 Myr in NSCs of late-type spirals is $2 \cdot 10^{-3}$ M$_\odot$/yr [26]. Assuming this SFR was constant for the past 10 Gyr, one would expect a stellar mass of $\approx 2 \cdot 10^7$ M$_\odot$ which is within a factor of 4 from the typical NSC mass of $5 \cdot 10^6$ M$_\odot$ [25]. Turning the argument around, if NSCs indeed build up their entire present-day mass via a series of repetitive starbursts, then they must have been in place at least 3 Gyr ago, unless their SFRs were significantly higher in the past than over the last 100 Myr. Given that observations to date are somewhat biased towards more luminous NSCs which likely have a time-averaged SFR higher than the “typical” NSC, this estimate might even be too low.

4. Do globular clusters form as NSCs?
As mentioned in the last section, most NSCs have likely formed a long time ago. In fact, some theories of structure formation suggest that already the first proto-galaxies undergo rapid nucleation [7], and form a dense star cluster at their center. If these proto-galaxies are gas-rich, the NSC will most likely experience multiple bursts of star formation similar to the present-day
NSCs in late-type disks. This process continues until the proto-galaxy is destroyed in a merger. Because of its compactness and high stellar density, the NSC will survive the merger, and from that moment on will passively age in the halo of the merger product. As discussed in [3], such a mechanism might explain the presence of multiple stellar populations observed in some high-mass globular clusters in the Galaxy. It is also consistent with the roughly constant specific frequency of GC systems and the observed mass fraction of GC systems in the local universe [16].

5. Connection to supermassive black holes
It has recently been proposed by [11] that NSCs extend the well-known scaling relation between the mass of a galaxy and that of its central super-massive black hole (SMBH) to lower masses. This has triggered speculation about a common formation mechanism of NSCs and SMBHs, being governed mostly by the mass of the host galaxy. The idea put forward is that NSCs and SMBHs are two incarnations of a “central massive object” (CMO) which forms in every galaxy. In galaxies above a certain mass threshold ($\approx 10^{10}\, M_\odot$), galaxies form predominantly SMBHs while lower mass galaxies form NSCs.

While tantalizing, this apparent connection opens more questions than it answers. For example, we know that some galaxies contain both an NSC and a SMBH. A well-known example is the “mini-Seyfert” NGC 4395 [12], but others have been found recently [20, 21]. Why then do some NSCs contain SMBHs, but not all? Why do some galaxies apparently contain neither NSC nor SMBH? Is an NSC possibly a pre-requisite for the formation of a SMBH? Is the formation of a BH (not necessarily a super-massive one) a logical consequence of the high stellar densities present in NSCs? Progress along these lines will require a better understanding of the formation of “pure” disk galaxies in the early universe, as well as improved models for the evolution of extremely dense stellar systems.

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