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Exploring the Star Clusters in the Centres of Galaxies with MUSE

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Massive star clusters are ubiquitous in the central regions of galaxies. For example, nuclear star clusters are present in most galaxies, and bulge regions can host globular clusters. Even though these star clusters are bright, studying their properties is limited by the underlying galaxy light. Here we discuss how integral-field spectroscopy with the Multi Unit Spectroscopic Explorer (MUSE) has enabled studies of the inner globular cluster systems of massive galaxies and how MUSE has allowed us to constrain the formation mechanisms of nuclear star clusters.

Introduction

The central regions of galaxies are home to many morphological structures, such as discs, bars or bulges, shaped by various processes. Within these structures, massive star clusters such as nuclear star clusters (NSCs) and globular clusters (GCs) can be embedded. Even though NSCs and GCs are both dense star clusters with millions of stars packed tightly together — and therefore inherently bright — studying those objects within the central regions of galaxies is challenging, owing to the underlying galaxy background. In photometric studies, the galaxy light is often modelled and subtracted to derive the colours and sizes of NSCs and GCs; however, such an approach is not possible with slit or multi-object spectroscopy. For this reason, spectroscopic studies of GC systems are usually limited to the outer regions of galaxies (for example, Forbes et al., 2017), and slit spectroscopy of NSCs is preferably done on bulgeless spirals or faint dwarf galaxies, where it is assumed that the host galaxy is not contributing significantly to the light in the centre (for example, Paudel, Lisker & Kuntschner, 2011; Kacharov et al., 2018).

The high spatial sampling combined with the wide field of view provided by the Multi Unit Spectroscopic Explorer (MUSE) instrument at the VLT has allowed us to circumvent these limitations. With MUSE data of nearby (< 50 Mpc) galaxies it has become possible to extract and analyse the spectra of star clusters nestled within the central regions of galaxies. As the host galaxy can be studied from the same data, a direct comparison between the stellar population and the kinematic properties of the host galaxy and its star clusters becomes possible. With such an approach, the inner star cluster systems of galaxies can be explored, and even the formation pathways of nuclear star clusters can be unveiled.

Probing inner globular cluster systems

GCs are dense star clusters, characterised by old stellar ages, which makes them powerful tracers of galaxy assembly and evolution. GCs within the bulge region of the Milky Way have recently been discussed as fossil remnants of bulge formation (Ferraro et al., 2021), but less is known about the GC populations in the inner regions of massive galaxies.

Fahrion et al. (2019) described the approach of extracting and analysing star cluster spectra from MUSE data using MUSE observations of FCC47 (NGC 1336), a nucleated elliptical galaxy in the Fornax cluster at a distance of 20 Mpc (Figure 1). Line-of-sight velocities of 24 GCs and metallicities of five GCs were measured. Fahrion et al. (2020b) then applied this method to data of 32 Fornax galaxies that were observed as part of the ESO Large Programme Fornax3D (Sarzi et al., 2018). In total, 733 GCs with reliable velocity measurements were found. For a subsample of 238 GCs metallicity measurements were also possible. With this sample, a non-linear translation between Hubble Space Telescope colours and metallicities was found (Fahrion et al., 2020c) and spectroscopic catalogues at larger radii from multi-object spectroscopy could be added (for example, Chaturvedi et al., 2022). Moreover, with this sample it was possible to test how well GCs trace the properties of the underlying host galaxy. Comparing the rotation amplitude and velocity dispersion of the GC systems with the rotation and dispersion of the host galaxies, it was shown that the red GCs in particular are good tracers of the motion of galaxy spheroids. Additionally, comparing GC metallicities with the host's metallicities at the projected positions of the GCs showed that these red GCs also follow the metallicity profile of the host.

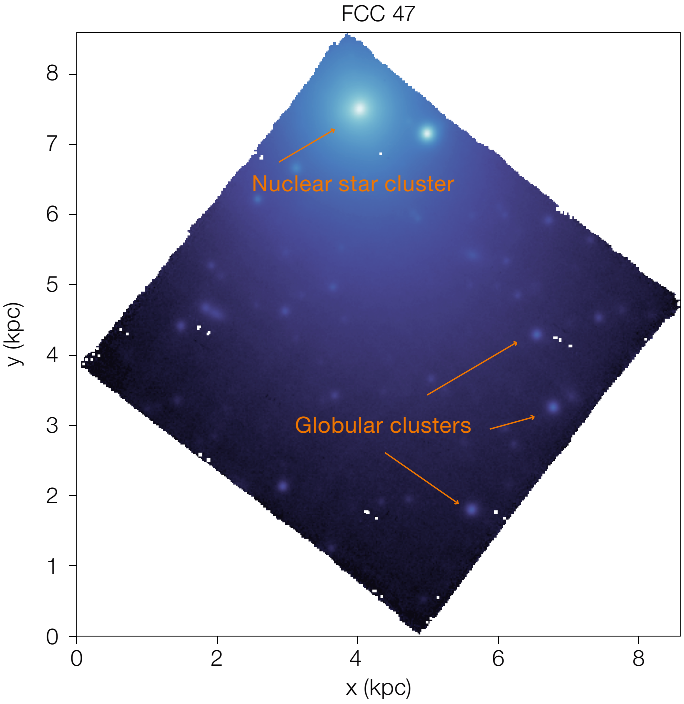

Figure 1. MUSE image of FCC 47 in the Fornax cluster with NSC and GCs highlighted.

Constraining nuclear star cluster formation

The formation of NSCs can be a complex process and typically two main pathways are discussed (see Neumayer, Seth & Böker, 2020 and references therein, and Figure 2): (i) formation through star formation directly in the galaxy centre, following the accretion and compression of gas, and (ii) via the mergers of massive star clusters. While these star clusters can be young clusters formed very close to the galaxy centre, traditionally the inspiral of GCs has been considered. In this way, NSC formation might be connected to GCs.

The *in-situ* or central star formation scenario depends on the mechanisms to funnel gas into the central region. Formation directly in the galaxy centre then has consequences for the NSCs formed in that way. For example, it can explain the presence of very young stars seen in the NSC of the Milky Way (for example, Schödel et al., 2020), and the formation from gas through dissipative processes explains the sometimes elongated, rotating and young NSCs in nearby spiral galaxies (Seth et al., 2006). As this process depends on the star formation activity in the galaxy centre, the NSC formed can show a complex, extended star formation history and can reach metallicities exceeding those of typical GCs as a result of being formed from already pre-enriched gas and metal-retention in the deep potential well of the galaxy centre. Complex star formation histories and high metallicities, however, can also be created when NSCs form through the rapid in-spiral of star clusters formed in the central region that then spiral in directly (for example, Guillard, Emsellem & Renaud, 2016), which might be an important channel at high redshift.

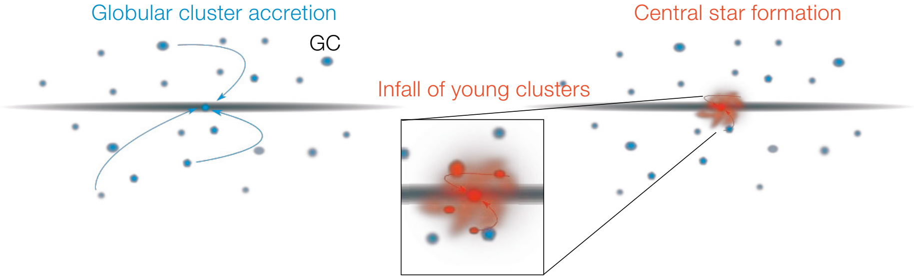

Figure 2. The two most discussed NSC formation channels: formation through the accretion and inspiral of GCs (left), and formation directly in the galaxy centre through in-situ star formation (right). In the latter, young star clusters might be formed first in the central region and then quickly spiral in (see the zoom-in).

On the other hand, formation through the mergers of GCs is a singular way to explain metal-poor populations within NSCs, for example as in the Milky Way (Do et al., 2020). This channel, in its purest form, only considers the dry merger of GCs and therefore no additional star formation is considered. As such, the NSC formed is expected to reflect the properties of GCs, which are characterised by old populations and low metallicities.

Dominant NSC formation channel

While there are indications that the NSC formation channel depends on galaxy mass and type (see Neumayer, Seth & Böker, 2020 for a discussion), to understand this process in individual galaxies the properties of NSCs and their hosts must be compared.

Using a similar approach as for the GCs, we can use MUSE data to study the stellar population properties of NSCs from background-cleaned spectra and compare them to the properties of the underlying host galaxy. This allows us to compare, for example, the NSC metallicity with that of the host. As a first example that this approach can unveil the dominant NSC formation mechanism, Fahrion et al. (2020a) studied two dwarf spheroidal galaxies observed with MUSE. In both cases, very metal-poor NSCs were found, even less enriched than the host galaxies. In the case of one dwarf galaxy, KK 197, the NSC even shares its low metallicity with a GC found near the centre, suggesting a formation from GCs spiralling into the centre. Building on this, Fahrion et al. (2021) then presented a larger sample of 25 early-type galaxies, mainly in Fornax, spanning a range of galaxy masses from 10^7 to 10^{11} $M_{\odot}$. Considering the metallicity differences between NSCs and hosts as well as NSC star formation histories, they found a clear transition in the dominant NSC formation (Figure 3). In low-mass galaxies ($< 10^9$ $M_{\odot}$), NSCs were found to be old and metal-poor and were likely formed through GC in-spiral, while in massive galaxies in-situ formation can explain their high masses, complex star formation histories and high metallicities. Interestingly, indications of both formation channels were found for intermediate-mass galaxies.

Regardless of this clear result, with only galaxies in a galaxy cluster the question arose whether this trend of NSC formation from GCs in dwarf galaxies would hold up in star-forming dwarfs. To address this, Fahrion et al. (2022) presented a novel sample of nine late-type dwarfs observed with MUSE. Even in this sample, the NSCs were found to be mainly old and metal-poor, and the contribution from additional *in-situ* star formation was small. This further confirmed that the NSCs in dwarf galaxies form from GCs and therefore closely resemble GCs in their properties. However, the star formation history of the galaxy imprints additional populations onto the NSC, which makes NSCs important records of past star formation episodes.

Conclusions

The MUSE instrument at the VLT has changed how spectroscopic studies of star clusters can be conducted. This is seen beyond the works mentioned in this article, as similar approaches have been used, for example, to study planetary nebulae in the central regions of galaxies (for example, Spriggs et al., 2021) or to explore globular clusters in dwarf galaxies (for example, Müller et al., 2020). Moreover, recent work has employed methods similar to those described here to analyse a larger sample of nucleated galaxies (Lyu et al., 2024), further confirming the trend with galaxy mass.

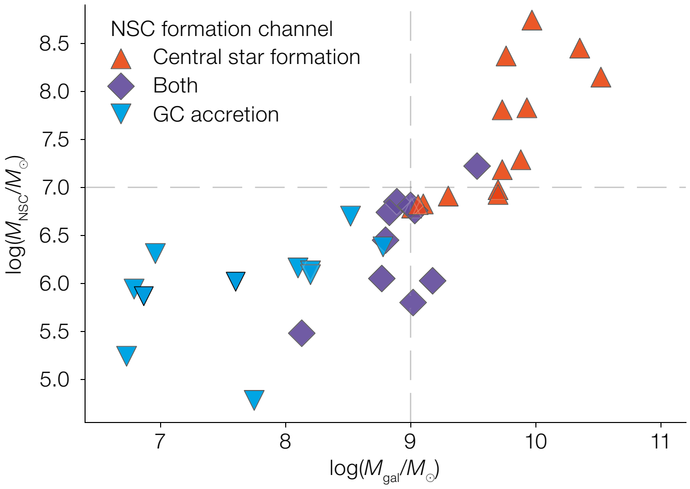

Figure 3. Dominant NSC formation channel as function of galaxy and NSC mass. Dwarf galaxies form their NSCs predominantly through the accretion of GCs, while the massive NSCs in massive galaxies form most of their mass through central star formation.

Nevertheless, unanswered questions remain. For example, it is unclear when NSCs and the observed trends in their formation pathways are established. Are the NSCs we see today already formed from then proto-GCs at high redshift? Or do the GCs form first and then merge in the later evolution? To answer these questions, the fraction of galaxies with a nuclear star cluster at higher redshift would be needed, but no such observations have yet been made. Additionally, it is unclear why some galaxies have GCs but no NSC. The lack of NSCs in high-mass galaxies might be explained by interactions with supermassive black holes (SMBHs), but the dynamical friction timescales are so short in dwarfs that NSCs formed through GCs should be ubiquitous. Perhaps galaxy interactions or the underlying dark matter profile might hinder such an in-spiral, but conclusive results even for individual systems are still missing (for example, Meadows et al., 2020). Another avenue is to couple detailed orbit-based dynamical models of galaxy nuclei with stellar population parameters. Looking into the orbital distribution of NSCs can give us important hints about the evolutionary history of the galaxy nucleus. In turn, this can enlighten us about whether the scaling relations between galaxy nuclei and host galaxy properties are driven by physical processes, like AGN feedback, or statistical ones, involving many subsequent mergers of galaxies and their NSCs and/or SMBHs.

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This image shows a pair of overlapping spiral galaxies, NGC 3314a and b, in the top left, caught in a majestic cosmic dance — captured by ESO's VLT Survey Telescope (VST).