Formation, evolution, and survival of massive star clusters
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The Assembly History of the Milky Way Nuclear Star Cluster

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Abstract. Within the central 10 pc of our Galaxy lies a dense cluster of stars, the nuclear star cluster. This cluster forms a distinct component of our Galaxy. Nuclear star clusters are common objects and are detected in ∼75% of nearby galaxies. It is, however, not fully understood how nuclear star clusters form. The Milky Way nuclear star cluster is the closest of its kind. At a distance of only 8 kpc we can spatially resolve its stellar populations and kinematics much better than in external galaxies. This makes the Milky Way nuclear star cluster the perfect local reference object for understanding the structure and assembly history of nuclear star clusters in general. There are of the order of 10^7 stars within the central 10 pc of the Galactic center. Most of these stars are several Gyr old late-type stars. However, there are also more than 100 hot early-type stars in the central parsec of the Milky Way, with ages of only a few Myr. Beyond a projected distance of 0.5 pc of the Galactic center, the density of young stars was largely unknown, since only very few spectroscopic observations existed so far. We covered the central $>4\,\mathrm{pc}^2$ (0.75 sq.arcmin) of the Galactic center using the integral-field spectrograph KMOS (VLT). We extracted more than 1,000 spectra from individual stars and identified >20 new early-type stars based on their spectra. We studied the spatial distribution of the different populations and their kinematics to put constraints on the assembly history of the Milky Way nuclear star cluster.

Keywords. Galaxy: center; kinematics; Stars: early-type, emission-line, Wolf-Rayet

1. Introduction

Nuclear star clusters (NSCs) were found in about 75% of low- to intermediate mass galaxies (Carollo *et al.* 1998; Böker *et al.* 2002; den Brok *et al.* 2014; Georgiev & Böker 2014). The typical effective radii of NSCs range from some pc to some tens of parsecs

(Böker *et al.* 2004; Côté *et al.* 2006; Georgiev & Böker 2014). They have masses in the range of 10^5 to 10^8 $M_\odot$ (Walcher *et al.* 2005; Ferrarese *et al.* 2006; Lyubenova *et al.* 2013). The NSC of our own Galaxy has a mass of 3×10^7 $M_\odot$ (Launhardt *et al.* 2002; Feldmeier *et al.* 2014; Schödel *et al.* 2014b) and an effective radius of 4.2 pc (Schödel *et al.* 2014a). Some galaxies contain a supermassive black hole (SMBH) within their NSC. The Milky Way (MW) is such a case, it hosts a black hole of 4.3×10^6 $M_\odot$ (Eckart *et al.* 2002; Ghez *et al.* 2005, 2008; Gillessen *et al.* 2009).

We study the stars of the NSC, in order to understand how and when mass was accreted by the center of the Galaxy, and to learn how the NSC and the SMBH grow. There are two different formation scenarios for NSCs: (1) Gas is accreted from the galactic disk. Then stars are formed from this gas in-situ, in the center of the galaxy (Milosavljević 2004; Pflamm-Altenburg & Kroupa 2009); (2) Stars form in massive star clusters outside the Galactic center. These clusters migrate to the center of the galaxy due to dynamical friction. There they merge and build the NSC (Tremaine *et al.* 1975; Capuzzo-Dolcetta & Miocchi 2008; Gnedin *et al.* 2013; Antonini 2013; Perets & Mastrobuono-Battisti 2014). But it is also possible, and probable, that both scenarios play a role in the formation of NSCs (Neumayer *et al.* 2011; Hartmann *et al.* 2011; De Lorenzi *et al.* 2013; Turner *et al.* 2012).

Once we understand how the MWNSC formed, it can serve as a reference object for understanding the formation of other NSCs. We follow two different paths. One is to study the stellar populations. Different stellar populations can tell us whether all stars formed at the same time, or in different star forming events. Secondly, we study the stellar kinematics. The stellar kinematics contain information about where the stars came from.

2. Young stars in the MWNSC are centrally concentrated

We observed the MWNSC using the K-band Multi-Object-Spectrograph (KMOS, Sharples *et al.* 2013). We observed $\sim$28 pc^2 of the MWNSC, out to the effective radius at 4.2 pc. Here we present first results from the analysis of the central $>$4 pc^2. We extracted spectra of more than 1,000 stars with a S/N$>$10. In addition to the spectra, we have photometry in the J, H, and K_S bands (Schödel *et al.* 2010, and in prep.).

Our data set contains spectra of 23 Wolf-Rayet (WR) stars and six narrow-emission line stars (Krabbe *et al.* 1995; Blum *et al.* 2003; Paumard *et al.* 2006; Tanner *et al.* 2006). These stars are young, massive and hot. Nine stellar spectra are featureless and show no spectral lines. These sources are young stars which lose mass through strong stellar winds. The winds interact with the interstellar medium and produce bow shocks (Geballe *et al.* 2006; Viehmann *et al.* 2006; Perger *et al.* 2008; Buchholz *et al.* 2009; Sanchez-Bermudez *et al.* 2014). We classified 76 stars as O/B stars. Their spectra have Brackett γ and He lines. Our data contain 24 new O/B stars, primarily at large radii.

We show the positions of the 114 young early-type stars in Fig. 1. 90% of the young stars are located within a projected distance of 0.5 pc to the central SMBH (Feldmeier-Krause *et al.* 2015). The young stars are less than 10 Myr old (Krabbe *et al.* 1995; Paumard *et al.* 2006; Lu *et al.* 2013).

We derive a lower limit for the total mass of the young star cluster of $M_{total,young} = 12{,}000\,M_\odot$. This result is in excellent agreement with Lu *et al.* (2013), who found $M_{total,young} = 15{,}000\,M_\odot$.

Most of the stars in our data set are cool late-type stars. Previous studies of the central parsec revealed that most of them are several Gyr old red giants (Blum *et al.* 2003; Pfuhl *et al.* 2011), and some are younger red supergiants. We have spectra of 980 such stars. Unlike the young stars, the late-type stars are spread throughout the cluster.

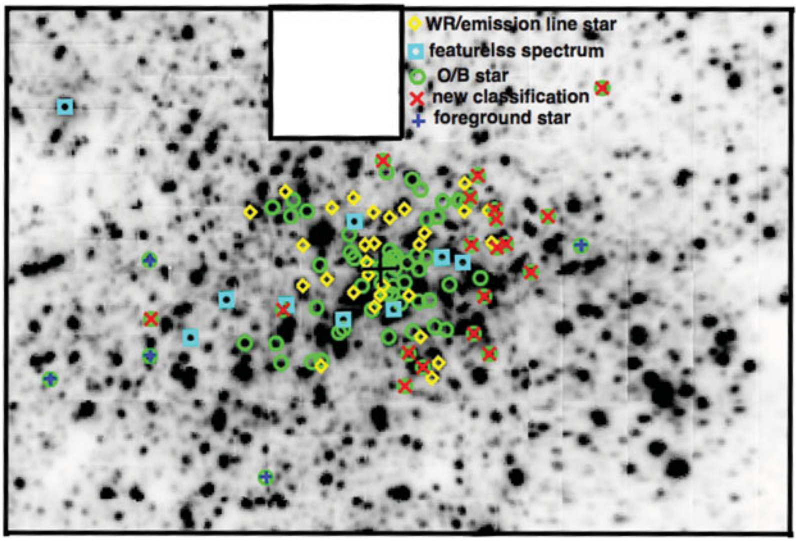

Figure 1. Spatial distribution of early-type stars in the MWNSC. The black box shows the KMOS field of view covering 2.51 × 1.68 pc, the small square in the upper middle was not observed due to the inactive IFU 13. The central black cross denotes the position of Sgr A*. Yellow diamond symbols denote confirmed WR and emission-line stars, cyan squares are stars with featureless spectra, green circles denote O/B stars. Red x-symbols indicate new young star candidates, blue plus-symbols probable foreground stars. Figure adapted from Feldmeier-Krause *et al.* (2015).

The fact that young stars are centrally concentrated suggests that these stars formed in-situ, in the center of the MWNSC. This is evidence against the infalling cluster scenario for these stars. If there was a cluster of young stars that fell towards the center, it must have lost many young stars on its way, due to tidal disruption. It would leave a trail of young stars, but we do not see such a trail. Therefore we favour the in-situ formation of the young stars of the MWNSC.

3. Stellar kinematics of old stars reveal complex structures

The stellar kinematics contain information about the origin of the stars of the MWNSC. We constructed a spectroscopic map of the central 9.5×8 pc of the MWNSC in integrated light using data obtained with the Infrared Spectrometer And Array Camera (ISAAC, Moorwood *et al.* 1998).

We derived the line-of-sight velocity and velocity dispersion of the unresolved faint stars (Feldmeier *et al.* 2014). The maps are shown in Fig. 2. The velocity map on the left panel reveals that the MWNSC rotates in the same sense as the Galaxy. The velocity dispersion map on the right shows an increase towards the central SMBH. We ran axisymmetric Jeans models and derived the total mass of the MWNSC $M_{MWNSC} = 3{\times}10^7\ \mathrm{M}_\odot$ (Feldmeier *et al.* 2014; Schödel *et al.* 2014b). The radius of influence of the black hole is at $2.3^{+2.1}_{-0.7}$ pc (Feldmeier *et al.* 2014).

The velocity map reveals a complex internal structure of the kinematics. There is a misalignment of the kinematic position angle by $9° \pm 3°$ relative to the photometry, which is aligned with the Galactic plane. This misalignment is found at radii from 1 to 4 pc. We further found indications for a substructure rotating perpendicular to the Galactic

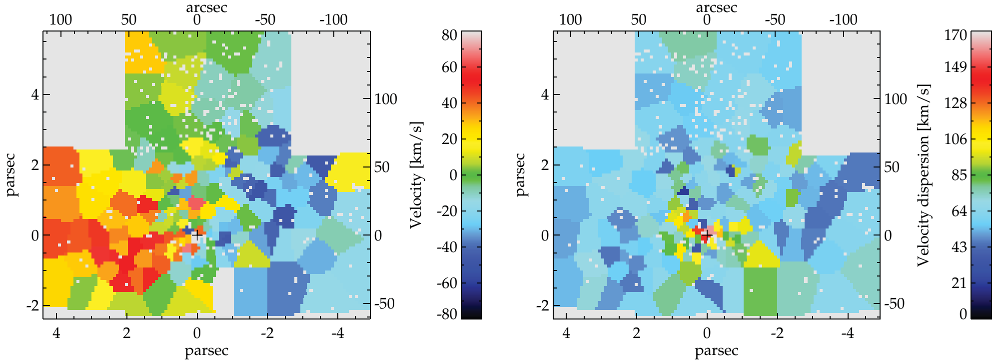

Figure 2. Large-scale kinematic maps of velocity and velocity dispersion (left, and right, respectively) in units of km/s. The coordinates are centred on Sgr A* and along the Galactic plane. The plus sign marks the position of Sgr A*. Figure adapted from Feldmeier *et al.* (2014).

plane at ~0.8 pc distance to the central black hole. This might indicate that the infall of massive star clusters contributes to the formation of NSCs (Feldmeier *et al.* 2014).

4. Summary

We looked at the stellar populations of the central 4 pc^2 of the MWNSC, and we found that young stars are strongly concentrated towards the center. This indicates that they formed there, in the center of the Galaxy. Further, we studied the large scale kinematics on 60 pc^2 of the MWNSC. We used the integrated light of the old stellar populations and found complex internal structures. Those structures may be the remnants of infalling massive star clusters.

There are still several open questions, and also a lot more data to analyse from the outer KMOS fields. We will study the metallicities of the cool, old stars. A metallicity spread as found by Do *et al.* (2015) shows that the late-type stars consist of different populations. We aim to investigate if there are spatial variations or gradients of the stellar population, and if the different stellar populations have different kinematics.

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