The nuclear star cluster of the Milky Way

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Abstract. The nuclear star cluster of the Milky Way is a unique target in the Universe. Contrary to extragalactic nuclear star clusters, using current technology it can be resolved into tens of thousands of individual stars. This allows us to study in detail its spatial and velocity structure as well as the different stellar populations that make up the cluster. Moreover, the Milky Way is one of the very few cases where we have firm evidence for the co-existence of a nuclear star cluster with a central supermassive black hole, Sagittarius A*. The number density of stars in the Galactic center nuclear star cluster can be well described, at distances \( r > 1 \) pc from Sagittarius A*, by a power-law of the form \( \rho(r) \propto r^{-\gamma} \) with an index of \( \gamma \approx 1.8 \). In the central parsec the index of the power-law becomes much flatter and decreases to \( \gamma \approx 1.2 \). We present proper motions for more than 6000 stars within 1 pc in projection from the central black hole. The cluster appears isotropic at projected distances \( r > 0.5 \) pc from Sagittarius A*. Outside of 0.5 pc and out to 1.0 pc the velocity dispersion appears to stay constant. A robust result of our Jeans modeling of the data is the required presence of \( 0.5 \sim 2.0 \times 10^6 \) \( M_\odot \) of extended (stellar) mass in the central parsec of the Galaxy.

1. Introduction

Nuclear star clusters (NSCs) can be found at the photometric and dynamical centers of the majority of galaxies. They are most easily identified in galaxies with low surface brightness. Imaging at high angular resolution, usually with the Hubble Space Telescope, has been an indispensable tool in the discovery and study of these objects [1–4]. NSCs have typically effective radii of a few parsecs, luminosities of the order \( 10^6 \sim 10^7 \) \( L_\odot \), and masses from a few times \( 10^5 \) to a few times \( 10^7 \) \( M_\odot \) [5; 6]. They are the densest known star clusters in the Universe. It appears that similar scaling relations exist between NSCs and the properties of their host galaxies as between supermassive black holes and their host galaxies [5; 7; 8]. For an overview of observational facts and theoretical ideas on NSCs, we refer the reader to Thorsten Böker’s review in this volume.

Figure 1 shows an image of a typical NSC, along with its light profile. It can be clearly seen how the NSC forms a highly compact, separate entity that sticks out from its galactic environment. An important problem in studying NSCs becomes apparent in Figure 1: NSCs being extragalactic objects, it is hard to study their properties in detail because they can be barely resolved with current telescopes and instruments. This situation will not change significantly with the advent of the next generation of extremely large telescopes. Even with a resolution that is improved by a factor of \( 5 \sim 10 \), we will still be limited to studying the integrated light of these objects. The interpretation of the data is therefore complicated because
NSCs are usually composed of stellar populations from repeated star formation episodes [6]. In many cases the most recent star formation event took place not more than a few million years ago.

![Image](ngc4701)

**Figure 1.** Example of a nuclear star cluster. Left: *HST* image of NGC 4701. The horizontal bar near the top of the image indicates a scale of 1 kpc. The symbol in the upper right corner indicates north (arrow) and east directions. Right: *I*-band surface brightness profile of the central 10″ of NGC 4701. Both images have been taken from [9]†.

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Studying the nuclear star cluster of the Milky Way offers the unique advantage of being able to resolve it into individual stars. With a distance of 8 kpc [10–13] to the Galactic center (GC), which will be assumed throughout this work, one arcsecond corresponds to ~ 0.04 pc. The Milky Way (MW) NSC can therefore be easily resolved. Observations of the GC at visible wavelengths are impossible (A_V ≈ 30 magnitudes, e.g., [14]), therefore all observations have to be carried out in the near- to mid-infrared. In this wavelength regime it is possible to reach scales of the order 1 milli-pc, with instruments such as the *HST*, but especially with adaptive optics (AO) assisted imaging on ground-based 8-10 m-class telescopes, like the Keck or ESO VLT telescopes.

The NSC at the center of our Galaxy is highly interesting for a further reason. Due to the observational difficulties involved in analyzing external NSCs, there are only a few cases where there is good evidence for the co-existence of an NSC with a central black hole, e.g. in the case of NGC 4395 [15] and a few other sources, e.g. [16; 17]. In case of the Galactic center, however, stellar orbits have provided the best evidence so far for the existence of a supermassive black hole, e.g. [11; 18; 19]. The mass of this black hole, coincident with the radio, X-ray, and infrared source Sagittarius A* (Sgr A*) has been determined with high precision to 4.0 ± 0.2 × 10^6 M_☉ (for a fixed GC distance of 8 kpc) [11; 13; 18; 20].

Although the GC has been a popular target of infrared observations since the earliest moments when this technique became available [21], it has not been realized for a long time that the MW contains an NSC. Although the NSC has been clearly detected in the first observations [21; 22], it has probably not been identified as such because of the difficulty in interpreting the observations due to an unfortunate combination of circumstances: low-angular resolution,
perspective from within the Galactic disk, strong and highly patchy extinction, and, above all, lack of the knowledge of the existence of NSCs, which became only observable in large numbers with the advent of the HST. Since the beginning of the 1990s, infrared (IR) observations of the GC were almost exclusively directed toward the central (half-)parsec, and therefore well within the NSC, in an effort to identify the central supermassive black hole of the MW. The first authors to point out the existence and derive the properties of the MW NSC were – to my knowledge – Launhardt et al. (2002) [23]. They derive an effective radius of several parsecs, a near-infrared (NIR) luminosity of $6 \pm 3 \times 10^7 L_\odot$, and a mass of $3 \pm 1.5 \times 10^7 M_\odot$ for the MW NSC. Spectroscopic and imaging studies have shown that there exist stellar populations of different ages in the central parsec of the GC. The two most recent star forming events have occurred about $10^8$ and a few times $10^6$ years ago, e.g. [24–28].

![Image of the nuclear star cluster of the Milky Way](image)

**Figure 2.** The nuclear star cluster of the Milky Way. Left: Near-to-mid-infrared composite image from observations of the *Spitzer Space Telescope* (Credit: NASA/JPL-Caltech/S. Stolovy (Spitzer Science Center/Caltech)). Right: Light profile of the central 500$''$ (19 pc at an assumed distance of 8 kpc) of the Milky Way. The profile was extracted from a 2MASS Ks-band image of the GC. No extinction correction was applied. The flux calibration may be subject to large systematic errors. The profile here is shown purely for illustrative purposes.

The currently available observational evidence therefore characterizes the MW NSC as a typical representative of its kind. An infrared multi-wavelength false-color image of the GC environment, acquired with the *Spitzer Space Telescope*, is shown in Figure 2. The NSC stands clearly out from its environment. The right panel of Figure 2 shows the light density vs. distance from Sgr A* as derived from 2MASS data [29]. It shows how the NSC sticks out from a rather flat background.

In this contribution we will present recent findings on the distribution and velocity dispersion of the stars in the central parsec of the Milky Way NSC.

### 2. Density structure

On large scales, the stellar density of the MW NSC can be well described by a power-law, $\rho \propto r^{-\gamma}$, with $\gamma \approx 1.8$ [21; 30–32]. Early speckle imaging observations at the ESO 3.5 m NTT indicated a cluster core with a radius of about 5$''$ or 0.2 pc [32; 33]. Some indication for a central density excess around Sgr A* was found in follow-up observations [34]. However, ten years later, AO observations at the ESO VLT showed unambiguously that the stellar density is not flat around Sgr A*, but rises further inward, although with a significantly smaller power-law index [35]. High angular resolution was decisive for this discovery because it reduces source confusion.
and thus the bias to underestimate the number of detected sources. In the following, we will refer to this excess of the stellar density above a flat core in the very center of the NSC as the cusp. This cusp is, however, not to be confused with a “classical” cusp that may build up in a stellar cluster around a black hole via two-body relaxation, e.g. [36–39]. First, classical cusp theory predicts a power-law index with $-1.5 \geq \gamma \geq -1.75$. This is significantly steeper than what has been found by observations [35; 40]. Second, it assumes largely passive evolution of an undisturbed cluster with a single-age stellar population. The latter is not the case in the MW NSC that has been marked by repeated episodes of star formation and contains various stellar populations (see introduction).

**Figure 3.** Left: Seeing limited ISAAC/VLT false colour near-infrared ($K_s + J$) image of the GC used for stellar number counts [40]. The white rectangle indicates the area where AO observations were used to derive the stellar number density of the cluster. Right: Stellar number surface density vs. projected distance, $R$, from Sgr A* [40]. The blue data points and error bars are surface number density measurements extracted from adaptive optics observations (NaCo/VLT) and include stars down to mag $K_s = 17.5$. Crowding and extinction corrections were applied to the data. The green data points are (crowding and extinction corrected) surface number densities from seeing limited observations (ISAAC/VLT). They include only stars down to mag $K_s = 16.0$ and have been scaled to match the AO data in the overlap region. See [40] for details. The dotted line indicates the power-law slope that has been found for the outer parts of the MW NSC in many studies ($\gamma = 1.8$). The pink dashed line is a fit to the all data with a single power law ($\gamma = 1.45$). It fails to fit the data in the innermost arcseconds. The straight line is a fit with a broken power-law, with the power-law index in the innermost arcseconds being $\gamma = 1.2$.

Further progress was achieved by an analysis that combined AO observations (NaCo/VLT) with a large FOV of about $40'' \times 40''$ – significantly beyond the cusp radius – and seeing limited observations (ISAAC/VLT) with a FOV of about $150'' \times 150''$, as well as applied an improved data analysis technique [40]. The left panel of Figure 3 shows a $J + K_s$-band false colour image of the corresponding ISAAC/VLT observations. A plot of the derived (crowding and extinction corrected) stellar surface number density vs. distance from Sgr A* is shown in the right panel of Figure 3. The stellar surface density can be fit very well with a broken power-law. Inside a projected break radius of $R_{br} = 6'' \pm 1''$, the power-law index is $\Gamma_{in} = 0.2 \pm 0.05$, outside $R_{br}$ the power-law index is $\Gamma_{out} = 0.75 \pm 0.10$. After de-projection, these values correspond to $\gamma_{in} = 1.2$ and $\gamma_{out} = 1.75$. The break radius cannot be constrained well after de-projection.
ranges between 15′′ − 30′′, but the assumption that there is a clear-cut break radius is in any case an over-simplification. The value for $\gamma_{\text{out}}$ is in excellent agreement with earlier findings on the power-law index of the MW NSC (see beginning of this section). The finding that the so-called cusp is extremely shallow explains why it has been mistaken as a flat core in earlier, lower-resolution observations.

Figure 4. $K_s$-band map of the GC, derived from AO observations with ESO’s NaCo/VLT (constructed from astrometric positions of the stars on 1 June 2006 and using a single point spread function for all stars). The arrows indicate the measured proper motions of the stars. See Schödel, Merritt & Eckart (2008, submitted to A&A) for details.
3. Velocity structure of the MW NSC

Several years of high-quality AO observations with a large FOV are now available from a large number of programs that have used NaCo at the ESO VLT to observe the GC. We have selected a suitable sub-set of these observations (11 runs from spring 2002 to spring 2008) to measure the proper motions of stars in the GC on a significantly larger FOV than what has been published in previous work. Details on the data processing are given in Schödel, Merritt, & Eckart (2008, submitted to A&A).

The proper motions of more than 6000 stars within 1 pc of Sgr A* were measured, with a mean uncertainty of just 12 km s$^{-1}$. The measured velocities of the stars on the plane of the sky are illustrated in the maps shown in Figure 4.

![Figure 5](image_url)

**Figure 5.** Left: Projected tangential (blue) and radial (green) proper motion velocity dispersion of stars with measured proper motions within 1 pc of Sgr A*. A GC distance of 8 kpc was assumed. See Schödel, Merritt & Eckart (2008, submitted to A&A) for details. Right: One-dimensional velocity dispersion of stars with measured proper motions within 1 pc of Sgr A*. It results from assuming isotropy and averaging the projected radial and tangential velocity dispersions. At $R > 12''$ the 1D velocity dispersion can be fit very well with a constant value. The dashed red line indicates what a pure Kepler law would look like in projection, assuming a broken power-law structure of the stellar cluster with a break radius $R_{\text{break}} = 20.0''$ (the exact value has no significant influence on the result) and $\gamma = 1.2$ inside and $\gamma = 1.75$ outside of $R_{\text{break}}$ (see section 2). The Kepler-law was fit to the data within $R = 5''$. It can be seen that the velocity dispersion profile cannot be fit with a Kepler-law over the entire radial range of the data.

The projected (with respect to Sgr A*) radial and tangential velocity dispersion vs. distance from Sgr A* was computed from the proper motions and is shown in the left panel of Figure 5. The projected tangential velocity dispersion is somewhat higher than the projected radial one in the region at $1'' < R < 6''$. Some net tangential streaming motion is also present in this region (not shown here, but see Schödel, Merritt, & Eckart, 2008, submitted to A&A). These findings are most probably related to the clockwise rotating disk of massive, young stars that has been identified around Sgr A* (see [27; 35; 41; 42] and contributions by Hendrik Bartko, Jessica Lu, and Thibault Paumard in this proceedings). At $R \gtrsim 8 - 10''$ the projected radial and tangential velocity dispersions become equal within the measurement uncertainties, providing evidence for an isotropic velocity structure of the MW NSC. Assuming isotropy, the one-dimensional velocity dispersion can be derived. It is shown in the right hand panel of Figure 5. A Keplerian fall-off of the velocity dispersion as it would appear in projection on the sky (assuming parameters for the cluster structure as discussed in section 2) is indicated in the plot. A pure Kepler law would be
expected if the gravitational potential were dominated merely by the mass of the supermassive black hole Sgr A*. The measured velocity dispersion deviates clearly from a Kepler-law at distances $R \gtrsim 12''$ ($R \approx 0.5$ pc). This indicates that the potential of the distributed mass of the stellar cluster must be taken into account when interpreting the measured velocity dispersion. At $R \gtrsim 12''$ ($\gtrsim 0.5$ pc) the velocity dispersion can be fitted very well with a constant value of $98.9 \pm 0.9$ km s$^{-1}$.

We applied isotropic and anisotropic Jeans models to the data. A robust result of these models is that they require the presence of $0.5 - 2.0 \times 10^6 M_\odot$ of extended (probably stellar) mass within 1 pc of Sgr A*, in addition to the mass of the black hole. The models cannot put strong constraints on the distribution of this mass, unfortunately. However, assuming that the mass is distributed in the form of a power-law, $\rho(r) \propto r^{-\alpha}$, the models allow for values $0 \leq \alpha \leq 1.5$. Values as large as $\alpha = 2.0$ appear to be safely ruled out.

4. Summary
The nuclear star cluster at the center of the Milky Way is the only such object in the Universe in which a significant part of its constituent stars can be observed individually. This situation will not even change with the advent of telescopes of the 30-60 m class in the next decades. The NSC at the GC is also of great interest because we know with certainty that the cluster at the GC co-exists with the supermassive black hole Sgr A*.

The density of stars in the MW NSC rises like a power-law with an index of $\gamma \approx 1.8$ toward Sgr A*. This slope becomes significantly flatter, however, in the central parsec, where it decreases to a value of $\gamma \approx 1.2$. Crowding is a serious problem in observations of the MW NSC, even when AO instrumentation on 8-10 m-class telescopes is applied. Current observations show a surface density of $> 20$ stars per square arcsecond within a projected radius of $R = 1''$ of Sgr A* (Figure 3). This number will certainly increase with further improvement of angular resolution.

We have measured the proper motions of more than 6000 stars within $R \approx 1$ pc of Sgr A*. These data supersede in quantity and quality any existing studies of this kind. The new proper motion data show that at $R \gtrsim 0.5$ pc the velocity dispersion ellipsoid is close to isotropic and can be fit very well by a constant value of $98.9 \pm 0.9$ km s$^{-1}$. A Keplerian fall-off of the velocity dispersion due to the point mass of Sgr A* can be observed unambiguously only at $R \lesssim 0.4$ pc.

Jeans models robustly require the presence of $0.5 - 2.0 \times 10^6 M_\odot$ at $R \leq 1$ pc in addition to the mass of the central black hole.

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