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The (quite dark) stellar cluster around the supermassive black hole Sagittarius A* at the center of the Milky Way

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Abstract. High-resolution seeing limited and adaptive optics near-infrared imaging observations of the stellar cluster within about one parsec of the massive black hole Sagittarius A* allow us to obtain a detailed picture of the structure of the nuclear star cluster of the Milky Way. We find that the stellar number counts and the diffuse light of the unresolved stellar population can be described very well by a stellar density function in the form of a broken-power law. This agrees well with theoretical predictions on the structure of a dynamically relaxed star cluster around a massive black hole. However, the cusp slope is found to be too shallow, which may be related to mixing of different stellar populations and continuous star formation, phenomena that are not taken into account by current theory. Mass densities larger than 10^7 solar masses per pc^3 are reached within 0.1 pc of the central black hole. Intriguingly, up to several tens of percent of the total cluster mass in the central parsec may be in the form of dark stellar remnants.

Keywords. Galaxy: center, Galaxy: nucleus, Galaxy: structure, infrared: stars, techniques: high angular resolution

1. Introduction

Nuclear star clusters (NCs) appear to be a common feature of most – if not all - spiral galaxies. They are apparently spherical clusters with luminosities in the range $10^5 - 10^8\,L_\odot$, effective radii of a few pc, and masses of the order $10^6 - 10^8\,M_\odot$ (see for example Böker, Sarzi, McLaughlin *et al.* 2004). Particularly intriguing is the recent finding that the scaling relationships between the masses of the central supermassive black holes and the properties of the host galaxies (bulge mass or luminosity), on the one hand, and between the black holes and the properties of the nuclear star clusters, on the other hand, are very similar (Côté, Piatek, Ferrarese *et al.* 2006; Wehner & Harris 2006; Rossa, van der Marel, Böker *et al.* 2006).

The center of the Milky Way plays a unique role in the exploration of galaxy centers because with its mere 8 kpc distance it can be observationally resolved down to light-day scales. Therefore it represents not only the most ironclad case for the existence of a supermassive black hole (see e.g. Eckart & Genzel 1996; Genzel, Pichon, Eckart *et al.* 2000; Ghez, Morris, Becklin *et al.* 2000; Schoedel, Ott, Genzel *et al.* 2003; Ghez, Duchêne, Matthews *et al.* 2003), but is also the natural template where we can study an NC and its constituents in detail. In this contribution we focus on the density structure of the Milky Way NC, particularly on the issue whether it displays a cusp-like structure around the central black hole (BH), termed Sagittarius A* (Sgr A*).

The relaxation time of the Galactic Center (GC) NC is of the order one to a few 10^9 yr, i.e. shorter than the age of the Galaxy (see, e.g., discussion in Schödel, Eckart, Alexander *et al.* 2007). Therefore one can expect that a collisionally relaxed cusp has formed around the supermassive BH. A cusp formed by two-body relaxation is predicted

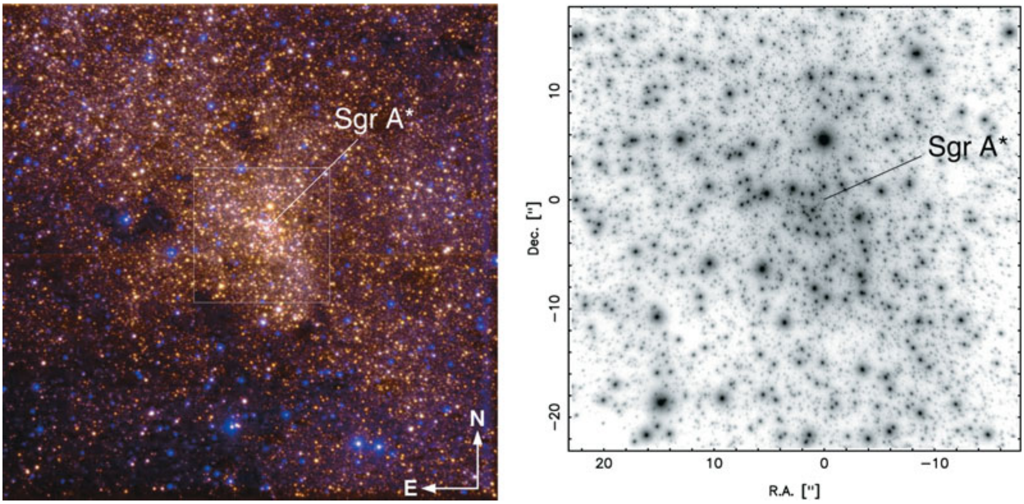

Figure 1. The left color image shows a composite of seeing limited observations with ISAAC/VLT in the J and K-bands. Blue stars are foreground stars. The white rectangle indicates the field-of-view of the AO-assisted K-band image observed with NACO/VLT, which is shown in the right panel. For details see Schödel, Eckart, Alexander *et al.* 2007.

to be characterized by a density distribution in form of a power law: $\rho \propto r^{-\gamma}$, where ρ is the stellar number density and r the three-dimensional distance from the black hole. The power-law index is expected to lie in the range $-3/2 \leqslant \gamma \leqslant -7/4$ (see Bahcall & Wolf 1977; Lightman & Shapiro 1977; Murphy, Cohn & Durisen 1991). The extent of the cusp is expected to be 0.1 to 0.2 times the influence radius, $r_{\rm BH}$, of the BH, where $r_{\rm BH}$ encloses a spherical volume that contains about twice as much stellar mass than the mass of the BH (see Merritt 2006).

The first successful attempt to identify the cusp around Sagittarius A* was undertaken by Genzel, Schödel, Ott *et al.* (2003). They described the shape of the NC by a broken power-law with an index $\gamma = 1.3 - 1.4$ and a break radius of $10''$ or ≈ 0.4 pc. Schödel, Eckart, Alexander *et al.* 2007 continue the work of Genzel, Schödel, Ott *et al.* (2003) and address several central issues, that had remained unresolved before. To mention some of them: use of a homogeneous data set with a larger field-of-view, analysis of star counts *and* of the diffuse light density, improved source detection and PSF fitting, non-parametric methods, and mass segregation. In this contribution we present some central results of their work.

2. Data

Both seeing limited and adaptive-optics (AO) assisted imaging data were used for determining the star counts and the diffuse light density in the central parsec of the NC. The seeing limited observations were obtained with the ESO VLT using the ISAAC infrared camera in the J, H, and K-bands (resolution $\sim 0.5''$ FWHM). AO observations in the K-band (resolution $\sim 0.06''$) were acquired using the ESO VLT and the infrared camera/AO system NAOS/CONICA. The field-of-view of both the seeing limited and AO images is shown in Fig. 1. For further details on the data and their analysis please see Schödel, Eckart, Alexander *et al.* 2007.

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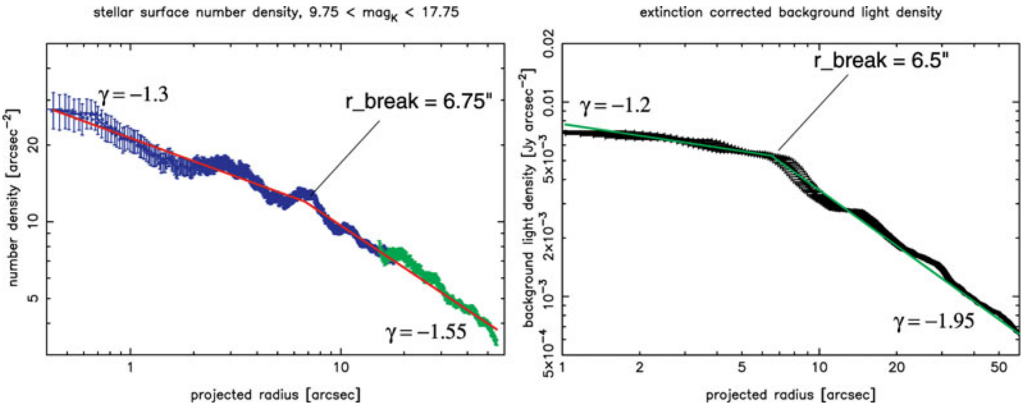

Figure 2. Left: Plot of stellar number density vs. projected distance from Sgr A* (after correction for crowding and extinction). The inner, blue data points were extracted from AO-assisted images, the outer, green data points from the seeing limited data (they were scaled to match the AO data points). The straight red line indicates the best broken power-law fit. Right: Plot of the diffuse light density (extinction corrected) in the seeing limited image vs. projected distance from Sgr A*. The straight green line indicates the best broken power-law fit (see Schödel, Eckart, Alexander *et al.* 2007).

3. Results and discussion

The structure of the central parsec of the NC was derived from the imaging data by several methods: star counts in AO-assisted and seeing limited images and analysis of the diffuse background light in seeing limited and AO-assisted data. A broken power-law provides an excellent fit in all cases. Figure 2 shows as an example plots of the star counts and of the diffuse light density, respectively, plotted vs. the projected distance from Sgr A* , along with the best fitting broken power-laws. The following overall best-fit

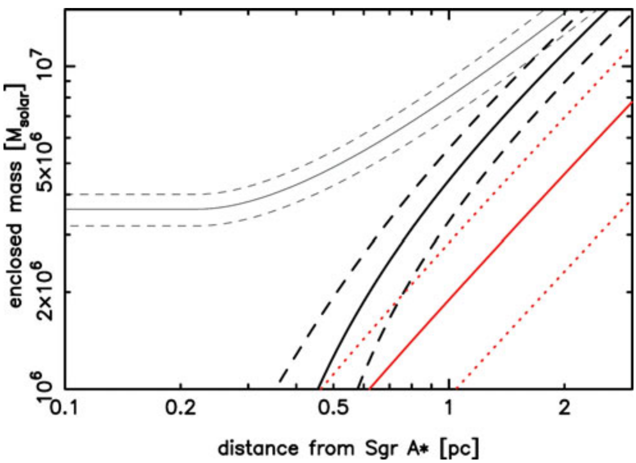

Figure 3. The grey line indicates a plot of enclosed mass vs. 3D-distance from Sgr A*, derived using the Bahcall-Tremaine mass estimator (Bahcall & Tremaine 1981) along with the derived broken power-law structure of the NC and assuming a constant velocity dispersion of $\sigma = 100.9 \pm 7.7\,\mathrm{km\,s^{-1}}$ (Figer, Gilmore, Kim *et al.* (2003)). The black line is the enclosed mass after subtraction of a BH mass of $3.6 \times 10^6\,\mathrm{M_\odot}$ (Eisenhauer, Genzel, Alexander *et al.* 2005). The red line is the visible total stellar mass derived from the star counts and the diffuse light density. Dashed lines indicate the $1\,\sigma$ uncertainties (see Schödel, Eckart, Alexander *et al.* 2007).

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parameters and uncertainties for the broken power-law result from a comparison between all applied methods: $r_{\rm break} = 6.0'' \pm 1.0''$ (0.22 ± 0.04 pc at the distance of the GC), $\gamma(r < r_{\rm break}) = 0.19 \pm 0.05$, and $\gamma(r > r_{\rm break}) = 0.75 \pm 0.10$.

The expected stellar cusp around the BH has been detected unambiguously. However, it is much shallower than what is predicted by theory. Most probably this is due to several simplifying assumptions in theoretical modeling, above all the assumption of an old, passively evolving stellar population. As found by several authors and discussed in Genzel, Schödel, Ott *et al.* (2003), for example, there is an important population of young, massive stars present in the central parsec of the Milky Way. In fact, continuous star formation is found to describe the stellar population in the GC best (see Figer, Rich, Kim *et al.* 2004). Theoretical models will have to be modified to include this fact.

Figure 3 shows a plot of the enclosed mass vs. distance from Sgr A*. After taking into account the mass of the BH and of the visible stars (from the star counts and the diffuse light), it can be seen that there is still a potential important deficit, amounting to several tens of percents, in explaining the observed extended mass of the NC. Possible candidates for this dark mass are stellar remnants, such as stellar mass black holes (see discussion in Schödel, Eckart, Alexander *et al.* 2007).

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