The structure of the nuclear stellar cluster of the Milky Way

Rainer Schödel\textsuperscript{1} and Andreas Eckart\textsuperscript{1,2}

\textsuperscript{1} I.Physikalisches Institut, Universität zu Köln, Zülpicher Str. 77, 50937 Köln, Germany
\textsuperscript{2} Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany

E-mail: rainer@ph1.uni-koeln.de

Abstract. The structure of the nuclear stellar cluster of the Milky Way is of particular interest because it is the densest stellar cluster in our Galaxy, where the theoretical prediction of the formation of a stellar cusp around the central supermassive black hole, Sagittarius A* (Sgr A*) can be examined. We present high-resolution adaptive optics observations with multiple intermediate band filters of the inner \(\sim 20\)'' around Sgr A*. From the images, stellar number counts and a detailed map of the interstellar extinction toward the central 0.5 pc of the Milky Way were determined. The extinction map is consistent with a putative southwest-northeast aligned outflow from the central arcseconds. An azimuthally averaged, crowding and extinction corrected stellar density profile presents clear evidence for the existence of a stellar cusp around Sgr A*. We show that the profile of the surface brightness density is dominated by the brightest stars in the central arcseconds and is different from the shape of the stellar cluster as inferred from the number counts. Several density peaks found in the cluster may indicate clumping, possibly related to the last epoch of star formation in the Galactic Center. There is evidence for a common proper motion of the stars in one of these clumps.

1. Introduction

The center of our Milky Way is located at a distance of 7.6 ± 0.3 kpc and contains a 3.6 ± 0.3 \times 10^6 M_\odot black hole (BH), Sagittarius A* (Sgr A*) \cite{16, 9, 7}. Theoretical work on stellar dynamics in a dense cluster surrounding a black hole that dominates the gravitational potential predicts the formation of a density excess, the so-called cusp around the BH. The density of a cusp that forms via two-body relaxation of the cluster is expected to be characterized by a power-law of the form \(\rho \propto r^{-1/2-7/4}\), where \(r\) is the distance to the BH \cite{2, 3, 11, 14}. First evidence for a cusp in the GC was found with NIR speckle imaging observations \cite{6, 1}. The first clear identification of the cusp around Sgr A* was achieved with adaptive optics (AO) imaging observations of the newly commissioned adaptive optics system/near infrared camera NAOS/CONICA (“NACO”) at the ESO VLT. It was found that the GC stellar cluster can be described by a broken power-law with \(\rho \propto r^{-2.0 \pm 0.1}\) outside of and \(\rho \propto r^{-1.4 \pm 0.1}\) inside of 10'' projected distance from Sgr A* \cite{8}. Here, we present an analysis of the GC stellar cluster that is based on new AO observations that cover a larger field-of-view (FOV) than in the previous work. Further improvements include improved source detection methods, taking extinction explicitly into account, analysing the two-dimensional structure of the cluster, and comparing the methods of star counts vs. surface brightness measurements.
Figure 1. Left: Sum of the 2.27 + 2.30 $\mu$m IB filter NACO images. The offsets from Sgr A* in right ascension and declination that are labelled on the coordinate axes serve as an orientation, but do not represent high accuracy astrometry because there may be a slight ($<1^\circ$) remnant rotation present in the images. North is up and east is to the left. Right: Adaptively smoothed, crowding and extinction corrected map of the stellar surface density. The smoothing was performed such that 40 stars contributed to the density at each point in the map. The smoothing radius varies between 0.6$''$ near Sgr A* and 2$''$ near the edge of the field. IRS 7, IRS 9 and IRS 16NE are particularly bright stars. The detection of faint stars is suppressed in their environment. The low density near these stars is therefore an artefact. IRS 13E is a compact group of co-moving stars, It coincides with a density peak. The circles around Sgr A* indicate radial distances of 3$''$ and 7$''$. At these distances several clumps appear to be concentrated. Note that bumps in the azimuthally averaged surface density can be seen at these distances in Fig. 3.

2. Observations
AO imaging observations were acquired with NACO/VLT in June and July 2004, using intermediate band (IB) filters of 0.06$\mu$m width, centered at 2.00, 2.06, 2.24, 2.27, and 2.30 $\mu$m. More details on the data and their processing can be found in Schödel et al. (2006, submitted to A&A). The program package StarFinder [4] was used for point source detection via PSF fitting. The left panel in Fig. 1 shows the sum of the IB 2.27 and 2.30 images, which was used for the extraction of the star counts.

3. Results
3.1. Extinction
The IB 2.00 to 2.27 $\mu$m images were used to construct a map of the interstellar extinction. The near-infrared (NIR) spectra of stars are largely free from strong emission or absorption features at these wavelengths. The slope of the SED at these wavelengths is therefore determined by the stellar temperature and interstellar extinction/reddening. Hot stars can be assumed to have Rayleigh-Jeans like SEDs in the NIR. Known hot stars in the FOV [15] were therefore used for photometric calibration. All stars of unknown type were assumed to have an intrinsic blackbody SED with a temperature of 5000 K. An extinction law $A_{\lambda} \propto \lambda^{-1.75}$ was assumed [5]. Foreground
The resulting extinction map is shown in Fig. 2. The 1σ uncertainty of the map is ≤ 0.1 mag, except in the regions with highest extinction, where it is ≤ 0.2 mag due to the reduced number of detected stars. A comparison with an extinction map derived from recombination lines [18] shows consistent results. The method presented here has the advantages that it is applicable in the absence of line emission, that it is not deteriorated near Sgr A* by the strong radio emission from this source, and that it provides a high spatial resolution. It is intriguing to note that the so called mini-cavity can be distinguished in the extinction map. It has been suggested in previous work that the mini-cavity is caused by fast winds from the Helium stars in the central arcseconds or by an outflow from Sgr A* [10, 13, 19]. The southwest-northeast aligned channel-like feature centered on Sgr A* in the extinction map is consistent with reduced extinction due to such a potential outflow from the central arcseconds along this direction (see also Muzic et al., this volume).
3.2. Stellar number density

The stellar number density was determined from the extracted stellar number counts. The counts were corrected for incompleteness due to crowding. The completeness was determined via the standard method of inserting and recovering artificial stars. The right panel of Fig. 1 shows the extinction corrected two-dimensional stellar surface density in the central 0.5 pc of the GC. It can be seen that the GC stellar cluster appears fairly circularly symmetric. A strong density peak is visible centered on Sgr A*. Some regions of reduced density can be attributed to the presence of extremely bright stars, such as IRS 7, that hinder source detection in their immediate environment. It can be also seen that the stellar surface density does not decrease in a homogeneous way from the center, but that there are several density peaks present in the field, preferentially located at radial distances of 3″ and 7″ from Sgr A* (see circles in right panel of Fig. 1 and bumps at 3″ and 7″ in Fig. 3). One of these clumps is coincident with the dense co-moving group of stars in the IRS 13E complex [12, 17].

The azimuthally averaged extinction and crowding corrected surface density is presented in Fig. 3. Masking and a corresponding correction were applied when the completeness of stars of a given magnitude was below 30% in any area of the field. The density was extracted in overlapping rings of increasing width and distance from Sgr A*. The smoothing width was determined from the smoothing radius at a given distance from Sgr A* that was applied when constructing the map of the two-dimensional surface density (see right panel in Fig. 1). Power-
laws were fitted to the plot of the stellar surface density. As can be seen in the Fig. 3, a broken power law is necessary in order to provide a reasonable fit in the central few arcseconds. The least-squares fit results in a broken power law with a break radius of $7 \pm 1''$, a power-law index of $\alpha = 0.6 \pm 0.1$ for the outer part, and of $\alpha_{\text{cusp}} = 0.25 \pm 0.1$ for the inner part of the cluster.

3.3. Number density vs. light density
In Fig. 4 we show a plot of the stellar surface density and of the stellar light density for stars in the magnitude ranges $9.75 - 17.75$ (left) and $14.75 - 17.75$ (right). Only the fainter 80% of the pixel brightness distribution was considered in order to dampen the influence of bright stars. While the light density distribution of the faint stars is similar to the stellar number density, there are considerable deviations when including the bright stars. This is the reason for the differences found in the structure of the GC stellar cluster when comparing number counts [8] and surface brightness [18]. The latter approach can lead to incorrect results in the inner arcseconds, that are dominated by bright, young stars. Analyzing the surface brightness of the GC cluster may be misleading due to the presence of bright stars that are not distributed in the same way as the faint population. This fact is further illuminated when analyzing the KLF.

The K-band luminosity function (KLF) of the cluster is shown in the left panel of Fig. 5. The right hand of Fig. 5 illustrates the percentage of the total light of the cluster that is contributed by stars of a given brightness, when assuming a simple power-law form of the cluster (dotted line in the KLF). The light from stars fainter than mag$_K = 15$ contributes $\leq 1.5\%$ to the total light, i.e. the cluster light is completely dominated by the bright stars, which may not follow the overall distribution of the cluster stars. Via the PSF wings, the bright stars contribute to the diffuse light in AO or even completely diffraction limited images. This may be especially problematic when dealing with observations of lower resolution (e.g. with HST compared to NACO/VLT in the NIR), where crowding of the sources is significantly increased.

3.4. A new co-moving group of stars?
A stellar density peak coincides with IRS 13E (see Fig. 1). This co-moving group of stars may be the remnant core of a stellar cluster [12, 17, 15]. We have identified a potential second dense
Figure 5. The left panel shows the K-band luminosity function (KLF) of the GC stellar cluster as it was obtained from AO observations with NACO. The dashed line indicates the raw counts, the straight line the completeness corrected counts. The ‘bump’ at mag$_K$ = 15.25 is due to red clump/horizontal branch stars. The dotted line indicates a power law fit to the data – ignoring the red clump bump – with a power law index 0.23 ± 0.02. The right panel illustrates the fraction of the total light of a star cluster that is contributed by stars of a given magnitude, under the assumption that the cluster LF is a power law. Here, the power law derived from the KLF in the left panel above was used.

4. Summary

Based on new AO observations, we present a detailed analysis of the structure of the stellar cluster in the central 0.5 pc of the Milky Way. The main results are as follows:

- A detailed map of the interstellar extinction in the central 0.5 pc is presented. It is consistent with a hypothetical SW-NE aligned outflow from the central arcseconds.
- A two-dimensional map of the stellar surface density, corrected for extinction and crowding, shows that the GC cluster is largely spherically symmetrical, but not homogeneous. Some density clumps are present, especially at projected distances of 3″ and 7″ from Sgr A*.
- The cusp around Sgr A* is detected with high significance. A broken power law with $r_{\text{break}} = 7″ \pm 1″$ and power law indices $\alpha_{\text{cusp}} = 0.25 \pm 0.1$, for the cusp, and $\alpha = 0.60 \pm 0.1$, for the outer cluster, provides a good fit to the data.
- Stellar light, even the diffuse one, is not a good tracer of the GC cluster structure because it is dominated by a few bright stars that are not distributed in the same way as the faint stars.
- We report the detection of a potential new co-moving dense group of stars, labelled the IRS15E-clump, located ∼12″ NNE of Sgr A*.
Figure 6. The left panel shows a zoom into the GC stellar cluster east of IRS15 NE. The right panel shows the potential co-moving group of stars that we call the IRS15E-clump. The arrows indicate the ±3σ uncertainties of the magnitude and direction of the proper motions of the stars, as measured from 4 epochs of AO images (2002 to 2004).

Acknowledgments
The authors would like to thank all people that helped in organizing the Galactic Center Workshop 2006.

References
[1] Alexander, T. 1999, Astrophys. J., 527, 835
[2] Bahcall, J.N. & R.A. Wolf 1976, Astrophys. J., 209, 214
[3] Bahcall, J.N. & R.A. Wolf 1977, Astrophys. J., 216, 883
[4] Diolaiti, E., O. Bendinelli, D. Bonaccini, et al. 2000, Astron. Astrophys. Supplement, 147, 48
[5] Draine, B.T. 1989, Proceedings of the 22nd Eslab Symposium held in Salamanca, Spain, 7-9 December, 1988, ed. B.H. Kaldeich, 93
[6] Eckart, A., R. Genzel, R. Hofmann, B.J. Sams, & L.E. Tacconi-Garman 1995, Astrophys. J., 445, L23
[7] Eisenhauer, F., R. Genzel, T. Alexander, et al. 2005, Astrophys. J., 628, 246
[8] Genzel, R., R. Schödel, T. Ott, et al. 2003, Astrophys. J., 594, 812
[9] Ghez A.M., G. Duchêne, K. Matthews, et al. 2003, Astrophys. J., 586, L127
[10] Lutz, D., A. Krabbe, & R. Genzel 1993, Astrophys. J., 418, 244
[11] Lightman, A.F. & S.L. Shapiro 1977, Astrophys. J., 211, 244
[12] Maillard, J.P., T. Paumard, S.R. Stolovy, & F. Rigaut 2004, Astron. Astrophys., 423, 155
[13] Melia, F., R.F. Coker, & F. Yusef-Zadeh 1996, Astrophys. J., 460, L33
[14] Murphy, B.W., H.N. Cohn, & R.H. Durisen 1991, Astrophys. J., 370, 60
[15] Paumard, T., R. Genzel, F. Martins, et al. 2006, Astrophys. J., 643, 1011
[16] Schödel, R., T. Ott, R. Genzel, et al. 2003, Astrophys. J., 596, 1015
[17] Schödel, R., A. Eckart, C. Iserlohe, R. Genzel, & T. Ott 2005, Astrophys. J., 625, L111
[18] Scoville, N.Z., S.R. Stolovy, M. Rieke, et al. 2003, Astrophys. J., 594, 294
[19] Yusef-Zadeh, F., D.A. Roberts, & J. Biretta 1998, Astrophys. J., 499, L159