The Galactic Center: Feeding and Feedback in a Normal Galactic Nucleus
Proceedings IAU Symposium No. 303, 2013
L. O. Sjouwerman, C. C. Lang & J. Ott
© International Astronomical Union 2014
doi:10.1017/S1743921314000611

The Milky Way nuclear star cluster beyond 1 pc

A. Feldmeier[1,9], **N. Neumayer**[1], **A. Seth**[2], **P. T. de Zeeuw**[1,8], **R. Schödel**[3], **N. Lützgendorf**[4], **M. Kissler-Patig**[5], **S. Nishiyama**[6] and **C. J. Walcher**[7]

[1]European Southern Observatory (ESO), Karl-Schwarzschild-Straße 2,
85748 Garching, Germany
[2]Department of Physics and Astronomy, University of Utah, Salt Lake City, UT 84112, USA
[3]Instituto de Astrofísica de Andalucía (IAA)-CSIC, E-18008 Granada, Spain
[4]ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[5]Gemini Observatory, 670 N. A'ohoku Place, Hilo, Hawaii, 96720, USA
[6]National Astronomical Observatory of Japan, Mitaka, Tokyo, 181-8588 Japan
[7]Leibniz-Institut für Astrophysik Potsdam (AIP), An der Sternwarte 16,
14482 Potsdam, Germany
[8]Sterrewacht Leiden, Leiden University, Postbus 9513, 2300 RA Leiden, The Netherlands
[9]email: `afeldmei@eso.org`

Abstract. Within the central 10 pc of our Galaxy lies a dense cluster of stars, the nuclear star cluster, forming a distinct component of our Galaxy. Nuclear star clusters are common objects and are detected in $\sim 75\%$ of nearby galaxies. It is, however, not fully understood how nuclear clusters form. Because the Milky Way nuclear star cluster is 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 a reference object for understanding the structure and assembly history of all nuclear star clusters.

We have obtained an unparalleled data set using the near-infrared long-slit spectrograph ISAAC (VLT) in a novel drift-scan technique to construct an integral-field spectroscopic map of the central $\sim$10×8 pc of our Galaxy. To complement our data set we also observed fields out to a distance of $\sim$19 pc along the Galactic plane to disentangle the influence of the nuclear stellar disk.

From this data set we extract a stellar kinematic map using the CO bandheads and an emission line kinematic map using H_2 emission lines. Using the stellar kinematics, we set up a kinematic model for the Milky Way nuclear star cluster to derive its mass and constrain the central Galactic potential. Because the black hole mass in the Milky Way is precisely known, this kinematic data set will also serve as a benchmark for testing black hole mass modeling techniques used in external galaxies.

Keywords. Galaxy: center, Galaxy: kinematics and dynamics

1. Introduction

Nuclear star clusters are distinct components of galaxies, lying in the center of the galaxy's potential (Böker *et al.* 2002, Neumayer *et al.* 2011). There are detections of nuclear star clusters in $\sim$75% of spiral galaxies (Carollo *et al.* 1998, Böker *et al.* 2002), and spheroidal galaxies (Côté *et al.* 2006). Nuclear star clusters have half-light radii of $\sim 3-5$ pc (Böker *et al.* 2004, Seth *et al.* 2006), and dynamical masses of 10^6-10^7 $M_\odot$ (Walcher *et al.* 2005). They consist of multiple stellar populations (e.g. Walcher *et al.* 2006, Seth *et al.* 2006, Rossa *et al.* 2006). Empirical studies (e.g. Rossa *et al.* 2006,

https://doi.org/10.1017/S1743921314000611 Published online by Cambridge University Press

Ferrarese *et al.* 2006) found a relation of galaxy properties, such as the dynamical mass of the galaxy, with the mass of either the central nuclear cluster, or the central supermassive black hole (SMBH). Nevertheless, there are also galaxies that contain both a nuclear star cluster and a SMBH. The most nearby case is our own galaxy, which contains a nuclear cluster of the mass $(3.0\pm1.5)\times10^7$ $M_\odot$ (Launhardt *et al.* 2002), and a SMBH with a mass of $\sim 4\times10^6$ $M_\odot$ (Ghez *et al.* 2008, Gillessen *et al.* 2009). The black hole measurements were obtained by resolving the orbits of individual stars in the central 1 pc of our Galaxy.

However, such observations are only possible as the distance to the Galactic center is only $\sim$ 8 kpc. In the case of extragalactic nuclear star clusters, we have to rely on other methods, and observations are based on integrated light measurements. Integral field spectrographs provide an excellent tool to observe spectra of the central parsecs of galaxies. Depending on the distance of the galaxy, the observations can extend out to $1-4$ times the half-light radius of the nuclear cluster. From these observations it is possible to extract information on the velocity moments of the line-of-sight velocity distribution (LOSVD) of stars. In combination with photometric data, dynamical models can provide information on the total mass of the nuclear star cluster and put constraints on the mass of a massive black hole in its center. For our own Galaxy, the Milky Way, there is no comparable data set. Most measurements of the nuclear star cluster are only isolated pointings on single stars, which gives no information on the underlying, faint stellar population. McGinn *et al.* (1989) observed the nuclear star cluster in integrated light along the Galactic plane out to ∼4 pc and ∼1.5 pc perpendicular to it. They derived velocity and velocity dispersion profiles along these axes using the first CO band head at 2.3 μm with a spectral resolution of 120 km s^{-1} and an aperture of 20$''$ diameter.

These data sets do not resemble the data we have for extragalactic nuclear star clusters. Therefore we set out to obtain a data set of the Milky Way nuclear star cluster that is similar to the observations of other nuclear star clusters, allowing us to measure the rotation law to larger radii than previous studies. As we have detailed information on the Milky Way nuclear star cluster from the observations of resolved stars, we can compare the results and identify potential biases in the methods used for other nuclear star clusters. Thus the Milky Way nuclear star cluster can serve as a benchmark for extragalactic nuclear star clusters.

2. Data

Our observations were performed with the longslit-spectrograph ISAAC at UT3/VLT. We observed a central field of $2'\times4'$ centered on Sgr A*, and a second field of $2'\times2'$ that partly overlaps with the first field along the minor axis towards the Galactic North. In addition we observed 6 smaller fields of $2'\times16''$ each at a distance of $4'$, $6'$, and $8'$ (corresponding to $\sim$ 10, 14, and 19 pc) from Sgr A* along the major axis. At about 10 pc, the influence of the nuclear stellar disk starts to dominate the mass profile (Launhardt *et al.* 2002). To cover this large area, we applied a drift scan technique. This means the telescope moved along the Galactic plane during the observations, and after scanning over $2''$, the detector was read out. We have 248 exposures in total. The observations are in the spectral range of $2.29-2.41$ μm, covering the stellar CO band heads and an H_2 gas emission line, with a spectral resolution R=4400, corresponding to 68 km s^{-1}.

After data reduction we put the central 200 spectra together in one data cube with a size of $4'\times3.5'$ ($\sim 9.6\times8.4$ pc), and a pixel size of $2.22''$. This data cube contains also foreground stars, therefore we constructed a second data cube where the foreground stars are removed. This is done using the 2MASS point source catalog (Skrutskie *et al.*,

https://doi.org/10.1017/S1743921314000611 Published online by Cambridge University Press

2006) and the catalog of IRSF/SIRIUS (Nishiyama *et al.* 2006). Both catalogs contain the magnitudes of stars in H and K band, and we apply color cuts to the stars. The pixels that are affected by these stars are replaced by zeros in the unbinned data, and then put together to a data cube of the same size as described before.

Our photometric data is from the *Spitzer*/IRAC Survey (Stolovy *et al.* 2006) at 4.5 μm. The image is dust and extinction corrected, and rebinned to a pixel size of $9''$/pixel (Schödel *et al.* in prep.). We measure the photometry and fit a two-dimensional surface brightness profile to the image using the *MGE_FIT_SECTORS IDL* package (Cappellari 2002). This routine was developed for galaxies but has also been successfully applied to nuclear clusters (e.g. Seth *et al.* 2010), and globular clusters (e.g. Lützgendorf *et al.* 2012; Feldmeier *et al.* 2013).

3. Results

We extracted the kinematics of the H_2 gas emission line of our data cube by fitting a single Gaussian to this line, and measured the velocity, velocity dispersion and flux. The maximum velocity in the northeastern lobe of the circumnuclear ring is $V_{LSR} = 103.3 \pm 0.5$ km s^{-1} (1-σ error of the fit), and the minimum velocity in the south-western lobe is -93.4 ± 0.4 km s^{-1}. These values, as well as the shape of the velocity and flux map, are in agreement with previous studies of H_2 gas emission (e.g. Yusef-Zadeh *et al.* 2001). The velocity dispersion map shows several regions of a velocity dispersion higher than 90 km s^{-1}. The region south of the southwestern lobe is the most extended region in our data set, and there the large velocity dispersion can be explained by a split of the H_2 gas emission in two distinct components. A double Gaussian fit obtains much better results, with a red-shifted component at $\sim$ 30 to 65 km s^{-1} and a blue-shifted component at ~ -80 to -45 km s^{-1}.

We obtain the stellar kinematics by fitting the LOSVD of the stellar CO band heads using the program *pPXF* (Cappellari & Emsellem, 2004), and the spectral library of Wallace & Hinkle(1996). The high-resolution spectra are convolved to a lower resolution, to match the ISAAC data. We can bin our data cube in many different ways, e.g. we apply exactly the same binning as McGinn *et al.*(1989). Alternatively we use Voronoi binning (Cappellari & Copin, 2003), to make sure that in each bin there is approximately the same signal-to-noise. With different values of the required signal-to-noise, we change the bin size. Thus we can simulate observations of an external galaxy with different spatial resolutions or different distances. We also bin the data in circular rings around Sgr A* and compute the root-mean-squared velocity $V_{RMS} = \sqrt{V^2 + \sigma^2}$, and we use this 1-dimensional profile for our Jeans modeling. We test these binnings for the data cube with the foreground stars, and the data cube from which we removed the foreground stars. We find that in $\sim$ 85% of all cases the difference in both velocity and velocity dispersion profile, is less than the uncertainty limits, which we obtain by running 100 Monte Carlo simulations. However, at small bin sizes, one star can easily dominate the integrated spectrum. Especially IRS 7, a supergiant with apparent magnitude $K \approx 6.5$, is so bright that it decreases the velocity dispersion in its bin significantly. Therefore we use the V_{RMS} that we obtain when excluding IRS7 and foreground stars.

With the surface brightness profile as input we run axisymmetric Jeans models to fit the data from the V_{RMS} profile, using the program written by Cappellari(2008). We assume an inclination of 90° (edge-on), and that the mass-to-light ratio (M/L) and anisotropy (β) are constant in radius. Then we fit the values of M/L, anisotropy β, and the black hole mass $M_\bullet$. Our preliminary best fit model is at a radial anisotropy of 0.6 with an $M/L_{4.5\mu m}$ of $0.32^{+0.28}_{-0.17}$ $M_\odot/L_{\odot,4.5\mu m}$, and a black hole mass of $M_\bullet = (2.0 \pm 1.0) \times 10^6$ $M_\odot$

https://doi.org/10.1017/S1743921314000611 Published online by Cambridge University Press

(1-σ uncertainties). Although the black hole mass is too low, it is in agreement with the result from direct measurements of stellar orbits. We also run models with a fixed value of $\mathrm{M}_\bullet = 4.0 \times 10^6\ \mathrm{M}_\odot$, and fitted the M/L as a function of radius.

4. Conclusions

By removing foreground stars from our spectroscopic data set and running the kinematic analysis with and without them, we showed that foreground stars do not significantly influence the kinematics when observing a nuclear star cluster edge-on. Our Jeans models with a constant M/L do not recover the correct black hole mass. This can be solved by fitting a dynamical M/L that is depending on radius. But to constrain the M/L as a function of radius, stellar population analysis is needed in addition to the dynamical measurements. Detailed stellar population analysis is not possible with our ISAAC data set due to the limited spectral range. However, we have a mosaic of the central $\sim 60'' \times 45''$ of the nuclear star cluster obtained with KMOS (VLT) covering the entire K-band. This data set will be used to probe the radial dependency of M/L, and to investigate the possibility of a stellar population gradient in the nuclear cluster of the Milky Way.

We also showed that dynamical Jeans models of the nuclear star cluster using constant M/L result in a black hole mass that is lower than the value from direct measurements. As our data set and methods are similar to those applied to nuclear clusters in other galaxies, we conclude that this is a hint to a systematic bias towards too low black hole mass measurements for these objects.

References

Böker, T., Laine, S., van der Marel, R. P., Sarzi, M., Rix, H.-W., Ho, L. C., & Shields, J. C. 2002, *AJ* 123, 1389

Böker, T., Sarzi, M., McLaughlin, D. E. van der Marel, R. P., Rix, H.-W., Ho, L. C., & Shields, J. C. 2004, *AJ* 127, 105

Cappellari, M. 2002, *MNRAS* 333, 400

Cappellari, M. & Copin, Y. 2003, *MNRAS* 342, 354

Cappellari, M. & Emsellem, E. 2004, *PASP* 116, 138

Cappellari, M. 2008, *MNRAS* 390, 71

Carollo, C. M., Stiavelli, M., & de Zeeuw, P. T. 1998, *AJ* 116, 68

Côté, P., *et al.* 2006, *APJS* 165, 57

Feldmeier, A., *et al.*, 2013 *A&A* 554, A63

Ferrarese, L., *et al.* 2006, *ApJ* 644, L21

Ghez, A. M., *et al.* 2008, *ApJ* 689, 1044

Gillessen, S., Eisenhauer, F., Trippe, S., Alexander, T., Genzel, R., Martins, F., & Ott, T. 2009, *ApJ* 692, 1075

Launhardt, R., Zylka, R., & Mezger, P. G. 2002, *A&A* 384, 112

Lützgendorf, N., Kissler-Patig, M., Gebhardt, K. Baumgardt, H., Noyola, E., Jalali, B., de Zeeuw, P. T., & Neumayer, N. 2012, *A&A* 542, A129

McGinn, M. T., Sellgren, K., Becklin, E. E., & Hall, D. N. B.. 1989, *ApJ* 338, 824

Neumayer, N., Walcher, C. J., Andersen, D., Sánchez, S. F., Böker, T., & Rix, H.-W. 2011, *MNRAS*, 413, 1875

Nishiyama, S., *et al.* 2006, *ApJ* 638, 839

Rossa, J, van der Marel, R. P., Böker, T., Gerssen, J., Ho, L. C., Rix, H.-W., Shields, J. C., & Walcher, C.-J. 2006, *AJ* 132, 1074

Schödel, R., Najarro, F., Muzic, K., & Eckart, A. 2010, *A&A* 511, A18

Schödel, R., Kunneriath, D., Stolovy, S., Feldmeier, A., Neumayer, N., & Nishiyama, S. *in prep.*

https://doi.org/10.1017/S1743921314000611 Published online by Cambridge University Press

Seth, A. C., Dalcanton, J. J., Hodge, P. W., & Debattista, V. P. 2006, *AJ* 132, 2539

Seth, A. C., *et al.* 2010, *ApJ* 714, 713

Skrutskie, M. F., *et al.* 2006, *AJ* 131, 1163

Stolovy, S., *et al.* 2006, *JPhCS* 54, 176

Walcher, C. J., *et al.* 2005, *ApJ* 618, 237

Walcher, C. J., Böker, T., Charlot. S., Ho, L. C., Rix, H.-W., Rossa, J., Shields, J. C., & van der Marel, R. P. 2006, *ApJ* 649, 692

Wallace, L. & Hinkle, K. 1996, *ApJS* 107, 312

Yusef-Zadeh, F., Stolovy, S. R., Burton, M., Wardle, M., & Ashley, M. C. B.. 2001, *ApJ* 560, 749

https://doi.org/10.1017/S1743921314000611 Published online by Cambridge University Press